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Firing of Coal and Limestone in a Low NO_x Burner To Reduce SO_2 Emissions

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K. Morris
F. R. Steward
M. Couturier

Energy Conversion Engineering Group

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Summary

Tests were conducted on sulfur capture and NO_x formation for the firing of Minto and Devco coal with limestone addition in a low NO_x burner.

The tests showed that the NO_x concentration in the stack gas decreased as the fraction of air fed as burner tertiary air increased for both Minto and Devco coal.

Tests conducted with limestone injected with tertiary air downstream from the burner gave more than a 50% reduction in NO_x stack gas concentration for both coals at all Ca/S ratios.

The tests showed that the NO_x concentration in the stack gas for a given staged air distribution was not affected by limestone addition.

The tests showed that a limestone addition with a Ca/S ratio of four could give greater than 60% reduction in SO_2 concentration in the stack gas for both Minto and Devco coal.

The injection of the limestone at a point downstream from the burner was found to be more effective with respect to SO_2 capture than injection in the tertiary air lines of the burner.

The blending of limestone with the coal before firing was found to give an SO_2 capture similar to downstream injection of the limestone.

Acknowledgements

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The probes used in this study were fabricated by Mr. Alfred Knappe, chief technician of the machine shop of the Chemical Engineering Department, University of New Brunswick.

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I. Introduction

Increasingly stringent federal guidelines on the emission of gaseous sulfur and nitrous oxides have led to new technologies for the combustion of coal. The New Brunswick Electric Power Commission with financial assistance from the Federal Department of Energy Mines and Resources-Canmet Division have constructed a pilot scale furnace at NB Power's Chatham Plant. This furnace is equipped with a specialized pulverized fuel burner known as a Low NO_x burner which stages the combustion air.

The coal indigenous to New Brunswick has a high sulfur content. When this coal is fired in conventional pulverized coal fired boilers correspondingly high emissions of sulfur oxides are generated. These boilers also produce significant levels of nitrous oxide (NO_x) emissions. Both SO_2 and NO_x are contributors to the formation of acid precipitation. The Low NO_x burner allows the combustion air to be staged thus lowering peak flame temperatures and producing reducing conditions within the high temperature part of the flame. These together lower NO_x emissions.

The use of a sulfur fixation agent such as limestone injected into the furnace can reduce SO_2 emissions. In addition, the reduction in flame temperature created by the staged combustion air can enhance the capture of sulfur by generating more reactive lime.

The test plan and results presented in this report provide information on the application of the Low NO_x burner to control emissions for possible use on existing and future pulverized coal fired boilers.

II. Unit Description

1.0 Furnace

The test furnace, shown in Figure 1, is constructed of eleven cylindrical modules each 2 feet high which gives an overall height of 22 feet. Each of the modules has a 40 inch O.D. carbon steel shell with 8 inches of refractory giving a two foot I.D. combustion chamber. In addition, each of the top four modules have two cooling water panels installed while the next five modules each have one cooling panel arranged in a staggered pattern. The furnace contains six sample probe access ports on modules 7, 6, 5, 4, 3, and 2.

The tenth module has a combustion gas exit duct leading to a cyclone. The cyclone is approximately 6 1/2 feet high with a 2 1/2 foot outer diameter. The cyclone has a refractory liner which reduces the inside diameter to 1 1/2 feet. The flue gas leaves the cyclone and enters a shell and tube heat exchanger where it is cooled to a low enough temperature to permit a 3 HP exhaust fan to force the gas through a stack and into the atmosphere. The fly ash separated from the flue gas in the cyclone falls into a hopper directly beneath the cyclone. This module also has an 8 inch pipe with attached U-bend. This U-tube is filled with water and acts as a furnace high pressure relief device and is vented to the atmosphere.

The eleventh module is a water cooled conical section which allows the bottom ash to drop to a storage hopper directly beneath it.

The cover of the furnace is refractory lined and accommodates the burner and four tertiary air lines. An observation port and ultraviolet flame detector are also contained on the cover.

Additional information on the construction of the test furnace can be found in an earlier report by Pierrynowski (9).

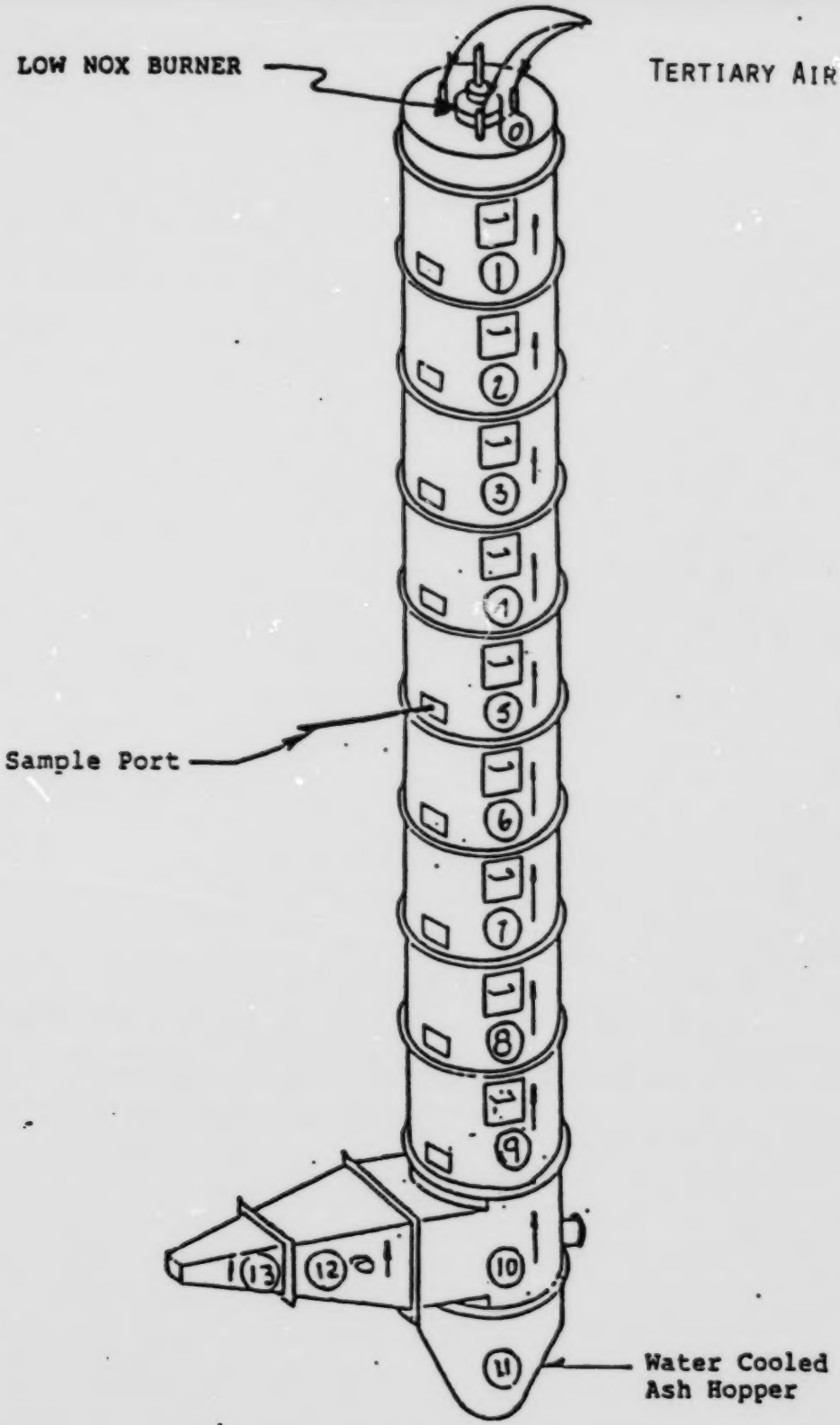


FIGURE 1: FURNACE SCHEMATIC

2.0 Feeding System Equipment

The feeding systems for the fuel and sorbent are virtually identical. The solids are loaded into a bin containing nine cloth filter bags which sit atop a 100 cubic foot capacity main hopper. The bin is sealed during normal operation. During loading a vacuum hose is attached to the intake of the bin. The suction of the solids into the bin is provided by the exhaust fan which is connected to the bin by carbon steel piping and isolation valves. High pressure air is supplied to the bin to permit manual pulsing of the bags so the solids drop to the main hopper beneath it.

The lower portion of the main hopper is conical and allows the solid to fall into a bin vibrator and an 8 inch pneumatic butterfly valve. The solids once through the butterfly valve enter a 1.5 cubic foot capacity screw feeder which feeds the material into a discharge chamber and into a nine pocket rotary air lock valve. The material from the rotary valve falls into an eductor placed in the primary air line for the coal system or the tertiary air line for the sorbent system. The appropriate amount of process air also passes through the eductors and entrains the solids, conveying them to the furnace.

The entire feed system sits on a deck weigh scale which indicates the amount of solids in the screw feeder hopper. The material is fed into the screw feeder in response to high/low limits set on the weigh scale. A sketch of the feeding system equipment is shown in Figure 2.

3.0 Burner

The burner known as a Low NO_x burner is constructed of carbon steel and is mounted on the top of the furnace. It consists of the primary air/fuel inlet line and four secondary air inlets. The secondary air, split into four inlets, enters the burner radially into a swirl generator. The swirl generator contains manually adjustable vanes to create turbulence within the secondary air. A schematic of the burner is shown in Figure 3.

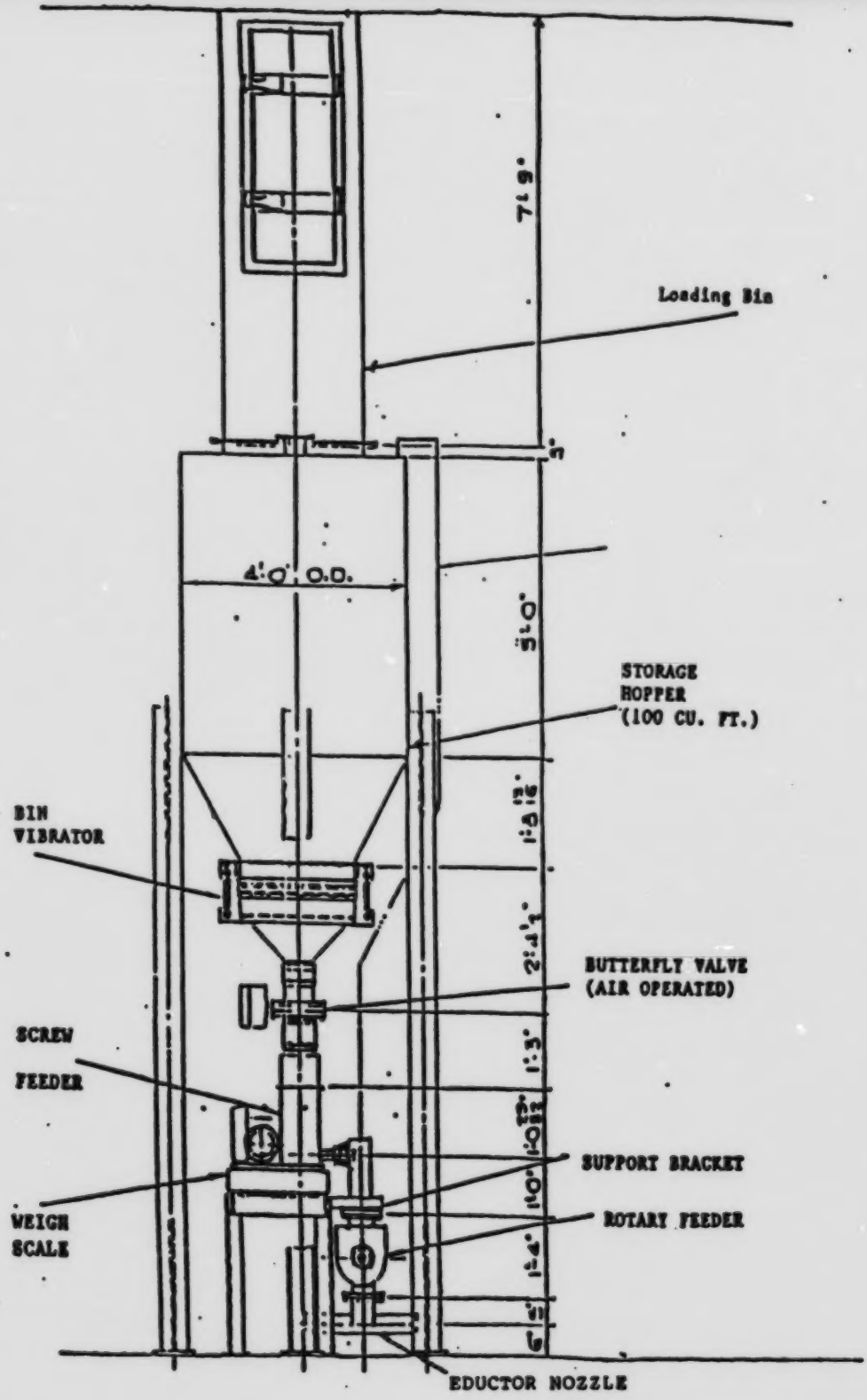


FIGURE 2: SOLID FEEDING SYSTEM SCHEMATIC

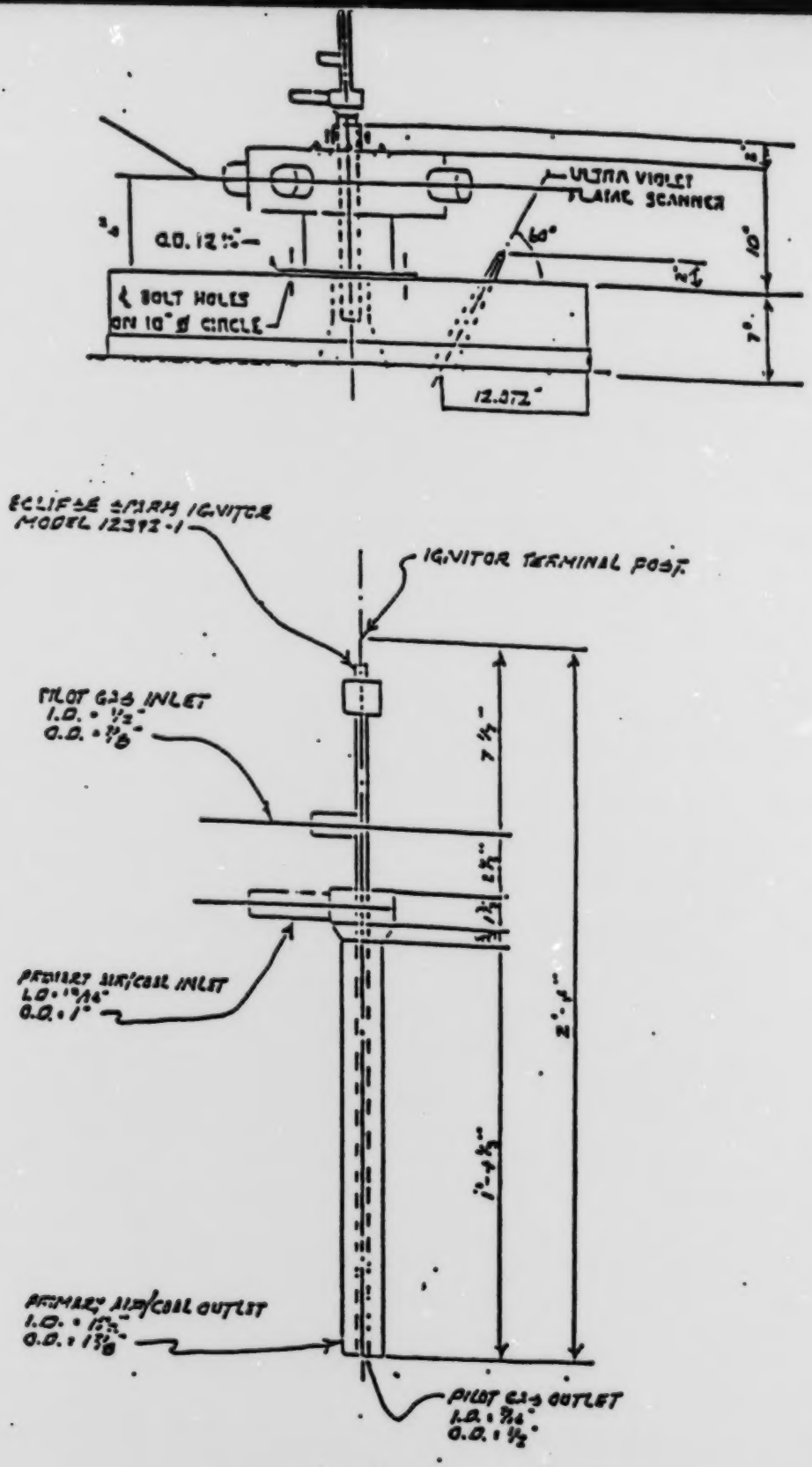


FIGURE 3: LOW NO_X BURNER

The burner also contains the propane preheat system. The propane enters the burner at a point above the primary air/fuel inlet and flows down through the center of the burner. The propane is ignited by a spark electrode which extends from the top to the bottom of the burner.

The burner has a maximum nominal capacity of one million Btu/hr.

4.0 Injection System

The combustion air is supplied by a positive displacement rotary blower with a 15 HP motor which produces air at 300 scfm, 7 psig and 160°F. The air provided by the blower is divided into three streams: secondary, tertiary , and bypass air.

The primary air is supplied by plant compressed air. The primary air entrains the coal in a 1 1/2 inch diameter line and carries it to the top of the furnace and feeds the coal from the top down through the center of the burner. The secondary air is split into four separate 2 inch lines and enters the burner radially from the side. The tertiary air entrains the sorbent and is split into four individual 1 inch diameter lines which enter the top of the furnace evenly distributed on an 18 inch diameter. The combustion air lines are constructed of schedule 40 carbon steel pipe with in line electric air heaters.

Initial tests involved injecting the limestone through the four tertiary air lines at the top of the furnace called "burner injection". Modifications were then made to change the injection point of the limestone to an elevation downstream of the burner where the optimum temperature for sulfur capture exists . The tertiary air line injection point was moved 7 feet downstream of the burner and split into two lines which entered on opposite sides of the furnace through wall ports. This was called "downstream injection".

5.0 Analytical Equipment

Analytical equipment consisted of a phase discrimination combustion gas extraction probe with conditioning system and gas analyzers, suction pyrometer, and particulate probe.

The phase discrimination gas sampling probe was constructed of stainless steel and had an outer diameter of 2 1/4 inches and a length of 5 feet. As shown in Figure 4 the probe was water cooled and equipped with a gas extraction line. An eductor drew the gas/solid mixture from the furnace into the probe. Some of the gas was withdrawn into the gas extraction line by a diaphragm pump. The remaining gas/solid mixture was returned to the furnace at a lower port hole by a flexible hose.

During the tests with high solid loadings, the gas extraction line plugged with solids from the furnace. This line was then capped and a cyclone was fitted onto the end of the probe. The eductor then drew the gas/solid sample through the probe and into the cyclone. The gas was separated from the solids in the cyclone and then sent to the analyzers via the diaphragm pump. The solids were removed from the bottom of the cyclone by the eductor and returned to the furnace.

The gases leaving the gas sampling probe were filtered and then conveyed to the gas analysis panel via a heat traced teflon line which maintained the gas temperature at 300°F to prevent water condensation. The diaphragm pump was located within the gas analysis panel at the end of the heated line and was also heated. After leaving the pump and prior to entering the gas analyzers the gas passed through a conditioning system to remove any moisture contained in the gas. The conditioning system involved passing the gas through a cooler which was set at a temperature of 2°C. Once through the cooler the dried gas entered an oven set at 85°C where it also passed through a filter. Once through the oven the gas sample proceeded to the gas analyzers. There were five analyzers to determine CO, CO_2, SO_2, NO_x and O_2.

The analyzers used were as follows:

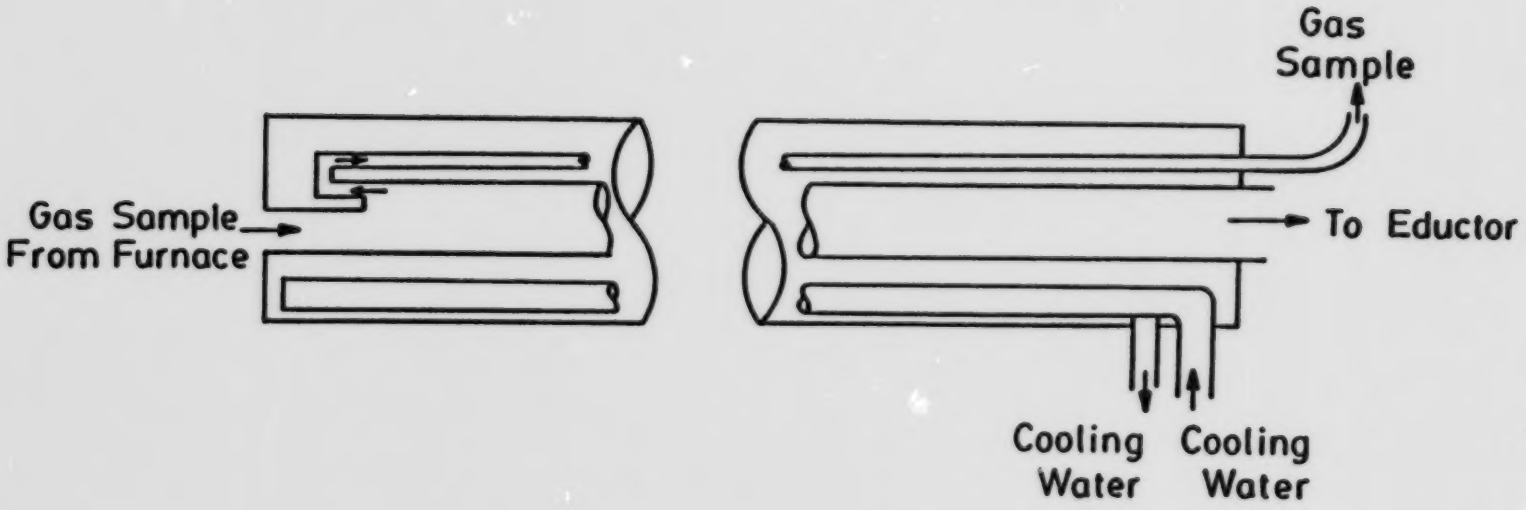


FIGURE 4: PHASE DISCRIMINATION GAS SAMPLING PROBE

CO Analysis:	Beckman Model 864 Non-Dispersive Infrared Analyzer.
CO_2 Analysis:	Beckman Model 864 Non-Dispersive Infrared Analyzer.
SO_2 Analysis:	Beckman Model 865 Non-Dispersive Infrared Analyzer.
NO_x Analysis:	Beckman Model 951A NO/NO_x Chemiluminescent Analyzer
O_2 Analysis:	Teledyne Analytical Instruments Model 326 RA

The suction pyrometer was constructed of stainless steel with an outer diameter of 2 1/4 inches and a length of 3 1/2 feet. This probe was also water cooled with a type R thermocouple surrounded by a ceramic insulator extended through it. The end of the suction pyrometer was a stainless steel shield that was not water cooled and contained the thermocouple tip. An eductor drew the gas/solid mixture from the furnace through the probe and then returned it back to the furnace. A schematic of the suction pyrometer is shown in Figure 5.

Also used for gas temperature measurements towards the end of the test program, was a type K sheathed thermocouple. This thermocouple was used to obtain temperature measurements under high solid loadings and at the far side of the furnace where the suction pyrometer could not reach.

The solids sampling probe was a water cooled stainless steel probe 5 feet long with a 2 1/4 inch outer diameter. The solids were collected in a ceramic filter housed in a filter assembly attached at the end of the probe. An eductor attached to the filter assembly drew the gas/solid mixture from the furnace through the probe and

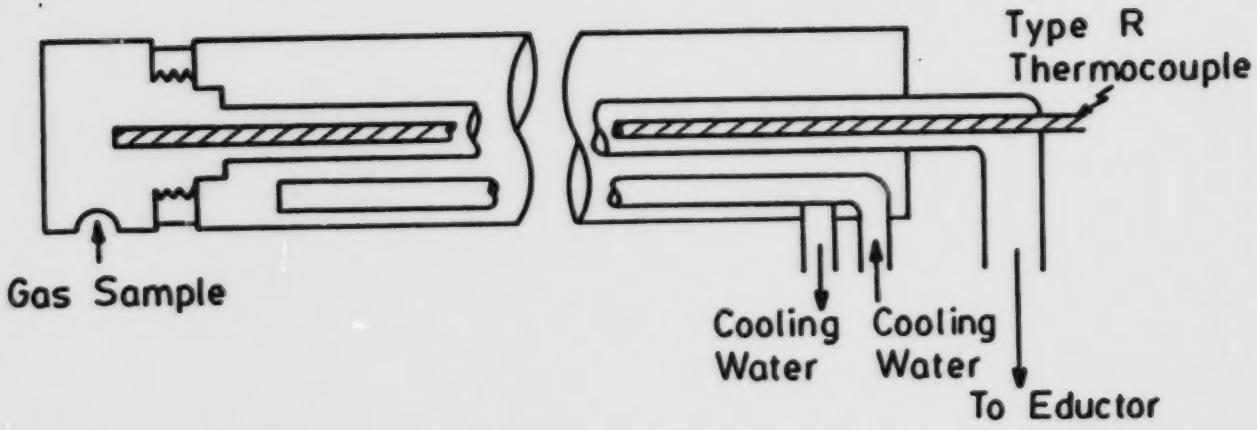


FIGURE 5: SUCTION PYROMETER

then returned the filtered gas sample to the furnace at a lower port hole. Nitrogen was supplied to the probe to quench any reaction that may take place between the gas and solid within the probe and to help carry the solid particles along the probe and into the ceramic thimble. A schematic of the solid sampling probe is shown in Figure 6.

Isokinetic sampling is achieved when the suction velocity at the tip of the probe is equal to the velocity in the furnace. The flowrate of the gases entering the probe was determined by measuring the total gas flow leaving the ceramic thimble with an orifice plate and subtracting from it the flow of quench nitrogen. This way it was possible to make adjustments to the total gas flow drawn by the eductor so as to maintain isokinetic conditions.

6.0 Instrumentation

The control of the combustion within the furnace and the corresponding auxiliary equipment was accomplished through the use of two MICON microprocessors. Each MICON was capable of handling eight loops with each loop controlling one parameter. The MICON may be used on automatic or manual control as well as being used as a data acquisition device. The parameters controlled by the MICON's for this project were the following:

-secondary air flow

-primary air flow

-tertiary air flow

-exit gas temperature

-primary air temperature

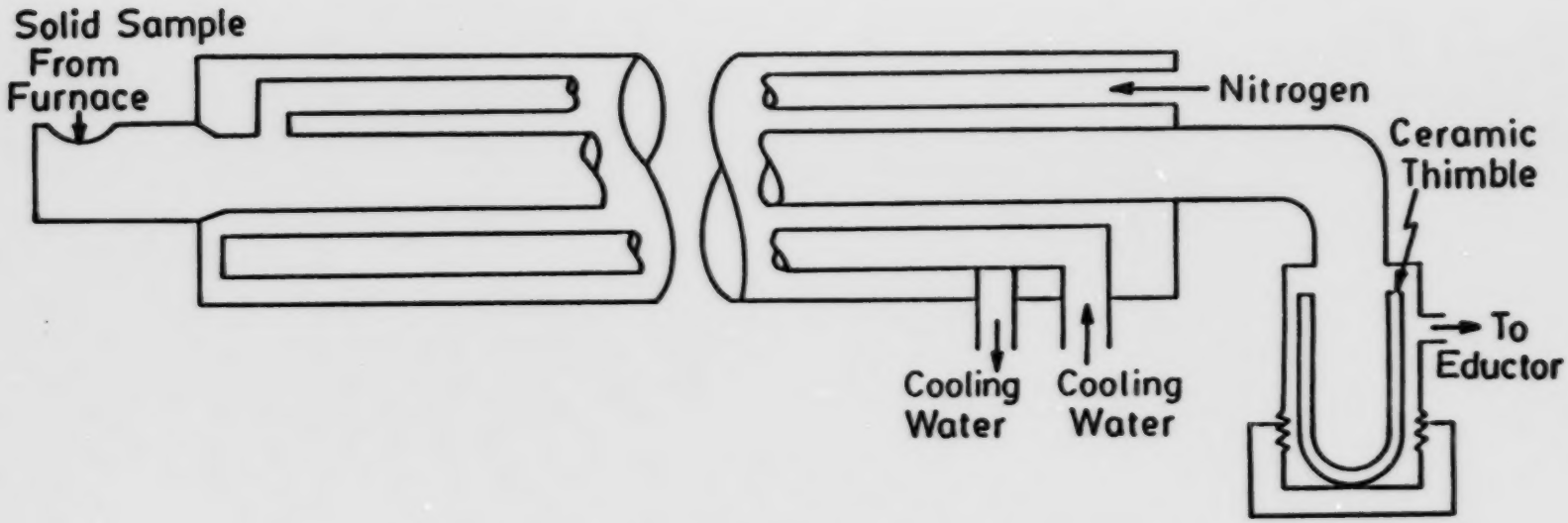


FIGURE 6: SOLID SAMPLING PROBE

-secondary air temperature

-tertiary air temperature

-coal feed rate

-sorbent feed rate.

There were propane safety controls which were utilized during the introduction and combustion of propane. Prior to the introduction of propane a purge switch would initiate a five minute purge cycle. The purge cycle was interlocked with the combustion and exhaust fans to ensure that both fans were operating. When the purge cycle was complete the propane ignition switch was depressed which opened a solenoid valve allowing the propane to flow into the furnace. If the propane ignited, an ultraviolet flame sensor would recognize this and the valve would remain open to continue the flow of propane. If a flame was not established within 15 seconds the solenoid valve closed and the purge cycle would have to be repeated. Once the flame had been established a closed circuit television system allowed the operator to observe the flame through an observation port situated at the top of the furnace.

The combustion and exhaust fans were interlocked such that the combustion fan would not operate unless the exhaust fan was operating. The fans were also interlocked with the rotary feed valves so that the valves would not operate unless the fans were operating. The screw feeders were interlocked with the rotary valves. The in line air heaters were also interlocked with the combustion fan.

A multi-channel chart recorder was the principle data acquisition device. This recorder was used to record and trend the following data points:

- temperatures from nine type R thermocouples embedded in the refractory wall of the furnace.

- flue gas temperature exiting the furnace.
- flue gas temperature exiting the exhaust fan.
- combustion air temperatures prior to entering the burner.
- water temperature exiting the heat exchanger
- output of the five gas analyzers.
- solids feed rate.

All process air flows were regulated by a pneumatic globe control valve and differential pressure orifice unit linked to the MICON control unit. Electric heaters were installed in each of the air lines. Other instrumentation included thermocouples embedded in the wall of each of the upper nine modules of the furnace.

III. Operating Procedure

1.0 Furnace

Two types of coal were tested in this project, Minto Coal (7%S) and Devco Coal (1%S). The coal to be used for a particular test was loaded into the main hopper of the feeding system prior to the beginning of a test.

The furnace was heated with propane for approximately 12 hours prior to the introduction of pulverized coal. A thermocouple in the refractory of module 3 was used to indicate the appropriate temperature for the introduction of coal. The propane heat-up rate was limited to 100°C/hr in the upper half of the furnace to prevent thermal damage to the refractory. Once a coal flame was established the propane was gradually phased out and eliminated once a steady flame was achieved. The air flows and solids feed rates were then adjusted to achieve the firing rate required. Two firing rates were examined, a high rate of 1 X 10^6 Btu/hr and a low rate of 0.6 X 10^6 Btu/hr. Excess combustion air was nominally maintained at 25% for all tests.

The initial series of tests consisted of the combustion of coal without the addition of limestone. These tests were conducted to establish the optimum operating conditions for combustion efficiency and the reduction of NO_x emissions. Initially the combustion air through the primary line was kept constant with the remaining air distributed between the secondary and tertiary lines. The distribution was varied from a high staging condition to a low staging condition. Once the optimum tertiary air flow was determined the air was sequentially diverted from the secondary air to the primary air. Once the optimum air flows for combustion efficiency and NO_x reduction were established the test program was directed to determine the effect of the addition of limestone.

For some tests the coal and limestone were pre-mixed at the appropriate molar calcium to sulfur ratio and fed into the furnace via

the primary air line. This pre-mixed material was referred to as blended fuel. The initial limestone injection tests had the tertiary air line entering into the burner, the tests with the addition of limestone through the burner in this way are referred to as burner injected tests. Subsequent tests involved moving the tertiary air line downstream of the burner, approximately 7 feet, and injecting the limestone at this point. These tests are referred to as downstream injection tests.

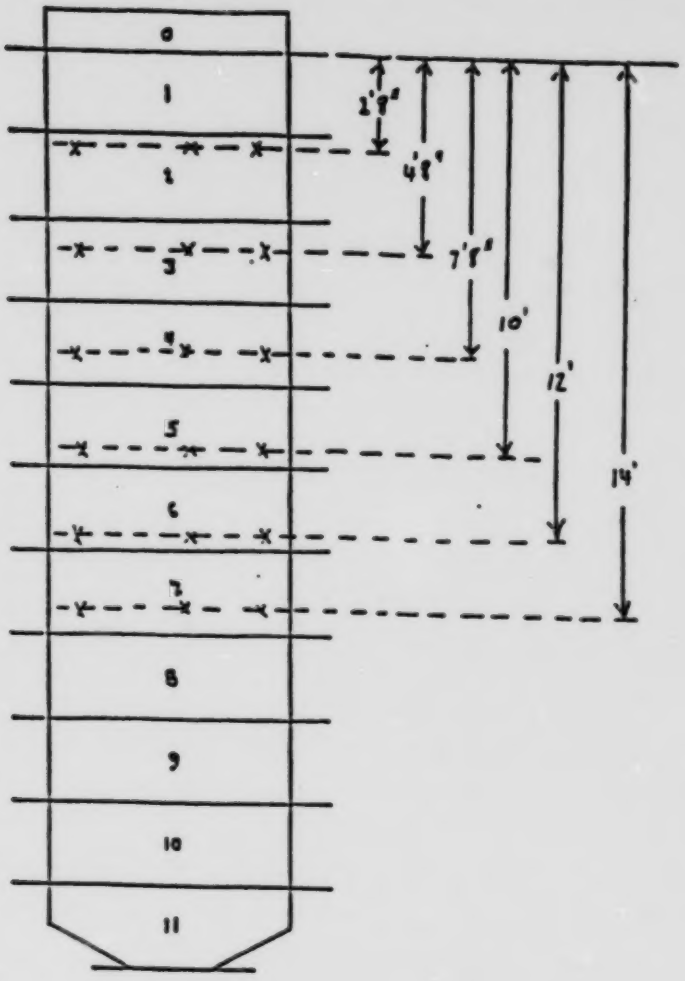
For limestone injected tests once a steady coal flame was achieved the limestone feed system was started and adjusted to achieve the required flow for the appropriate molar calcium to sulfur ratio.

2.0 Analytical Tests

Each test consisted of analyzing the combustion gas, measuring the combustion gas temperature, and collecting a quantity of ash from within the furnace. There were six sampling parts available on the furnace and when sampling three insertion depths were used. The elevations and depths available for sampling are shown in Figure 7.

Once coal combustion had been initiated and stabilized along with the appropriate amount of limestone, if required, a gas analysis was performed. The stainless steel gas probe was inserted into the furnace through a flange sealing arrangement to eliminate the possibility of contamination of the gas sample with ambient air. The gas sample was extracted from the furnace and transported to the gas analysis system where it was conditioned and analyzed for carbon dioxide, carbon monoxide, sulfur dioxide, oxygen, and nitrogen oxides. The gas analyzers were calibrated prior to the commencement of any tests.

The suction pyrometer, used for determining the temperature of the combustion gas, was then inserted into the furnace through the flange sealing arrangement. Temperatures were measured



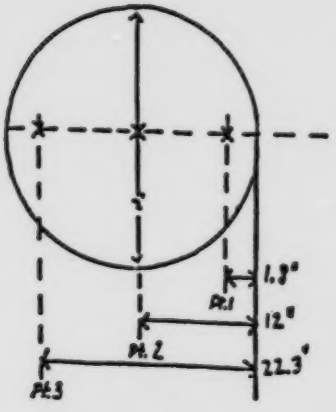


FIGURE 7: SAMPLING LOCATIONS ON FURNACE

axially and radially at several sample ports downstream of the burner.

An ash sample was taken from inside the furnace using the particulate probe. The bottom sampling port was used with the probe inserted to each of the three depths for approximately fifteen minutes each or until a sufficient sample was collected. Ash samples were also collected from the storage hopper directly beneath the furnace, "bottom ash", and from the hopper beneath the cyclone, "fly ash".

During a test the heat removal rate of the furnace was obtained by determining the amount of heat transferred to the cooling water in the cooling panels.

3.0 Procedural Problems

The major problem encountered during a test would be plugging of the probes with solids from the furnace.

The small gas extraction line of the phase discrimination gas sampling probe would frequently plug with solid material. When this line was even partially plugged the pressure of the gas sample supplied to the gas analyzers would decrease and this would significantly alter the concentration readings supplied by the analyzers. Initially the solids could be removed from the probe by blowing through with high pressure air. At high Ca/S ratios this failed to work and the probe had to be modified. The gas extraction line was capped and a small cyclone was attached to the end of the probe. The heated hose and filter was attached to the top of the cyclone to transport the gas sample to the analyzers by the pump. The solids separated from the gas by the cyclone were returned to the furnace. The addition of the cyclone to separate the gas/solid mixture resolved the plugging problem experienced with this probe.

To alleviate some of the plugging problem experienced with the suction pyrometer, the opening at the tip of the probe was pointed down the furnace away from the flow of solids instead of into the

flow of solids. Although this probe would plug frequently during a test, blow back with high pressure air through the probe would remove the solid material.

Plugging of the tip of the solid sampling probe with solids from the furnace would occur throughout a test. Plugging would cause a drop in the flowrate of the gas/solid sample being drawn from the furnace. As a result, isokinetic sampling was very difficult to achieve in many cases since the suction flowrate required to achieve isokinetic sampling would cause almost immediate plugging of the probe. To obtain a sufficient sample for analysis the suction flowrate was in many cases increased beyond what was required for isokinetic sampling conditions; this resulted in much less plugging of the probe. Blow back through the probe with high pressure air would remove any solid material that did get caught in the probe.

4.0 Laboratory Tests

The laboratory at the Chatham Plant is a fully equipped fuel and ash analysis laboratory. The analytical equipment available for fuel and ash analysis includes:

-proximate analyzer

-bomb calorimeter

-carbon, hydrogen, nitrogen analyzer

-sulfur analyzer

-atomic absorption spectrophotometer

-sieve screens and shaker

-oven and furnace

Prior to the beginning of any test a fuel sample was obtained and taken to the laboratory for an ultimate, proximate, calorific analysis and a particle size distribution. If a sorbent was used

during a test a sample of the sorbent was analyzed for CaO, MgO, and Fe_2O_3 as well as a particle size distribution.

The ash samples obtained during a test were subjected to a combustible content analysis and chemical analysis including $CaCO_3$ content.

IV Results

A matrix of test conditions is presented in Table 1. Appendix A includes the detailed results for each test. All tests give the gas composition at the outlet of the furnace, CO_2, O_2, CO, SO_2 and NO_x and the outlet temperature of the furnace at three positions. The values at each measuring position are in general averages of five determinations. A solid sample was collected at the furnace exit using three positions with a water cooled probe for analysis. The heat removal rate from the furnace walls was determined from cooling water flow rates and temperature rise measured for each cooling panel.

For some test runs with limestone addition the gas concentrations and temperature were measured at three levels in the furnace and at three positions at each level. At each position the values reported are in general averages of five determinations. A solid sample was collected at the furnace exit using three positions with a water cooled probe and sent for analysis. A solid sample was also taken from the bin collecting bottom ash and the bin collecting fly ash and sent for analysis.

The initial series of tests concentrated on establishing the optimum air distribution between primary, secondary, and tertiary air to reduce NO_x emissions and maintain a high combustion efficiency. Two firing rates were tested using both Minto and Devco coal, 0.6 X 10^6 Btu/hr and 1.0 X 10^6 Btu/hr. The results for Minto coal are presented in Figure 8 and the results for Devco coal are presented in Figure 9. Figures 8 and 9 show NO_x concentration versus the fraction of stoichiometric air through the tertiary air line, or from a low to a high staging air distribution. The fraction of air distribution is based on 1.00 for stoichiometric or 1.25 total for the 25% excess air used in all runs.

Once the air distribution for minimum NO_x emission was established testing continued with the addition of limestone to

Table 1 Operating Conditions for Tests Carried Out During Study

Test No.	Type of Coal	Firing Rate ($x10^6$Btu /hr)	Type of Limestone Feed	Ca/S Ratio	Air Distribution Fraction of Stoichiometric		
					Primary	Secondary	Tertiary
1	Minto	0.6	-	-	0.40	0.10	0.75
2	Minto	0.6	-	-	0.40	0.60	0.25
3	Minto	0.6	-	-	0.40	0.35	0.50
4	Minto	0.6	-	-	0.40	0.85	-
5	Minto	1.0	-	-	0.25	0.85	0.15
6	Minto	1.0	-	-	0.25	0.50	0.50
7	Minto	1.0	-	-	0.25	0.75	0.25
8	Devco	1.0	-	-	0.25	0.50	0.50
9	Devco	0.6	-	-	0.40	0.35	0.50
10	Devco	0.6	-	-	0.40	0.60	0.25
11	Devco	0.6	-	-	0.40	0.75	0.10
12	Devco	0.6	-	-	0.45	0.30	0.50
13	Devco	0.6	-	-	0.45	0.55	0.25
14	Devco	0.6	-	-	0.50	0.25	0.50
15	Devco	0.6	-	-	0.40	0.60	0.25
16	Minto	0.6	Blended	1.8	0.40	0.35	0.50
17	Minto	0.6	Blended	3.3	0.40	0.35	0.50
18	Minto	0.6	Blended	4.8	0.40	0.35	0.50
19	Devco	0.6	Blended	2.1	0.40	0.35	0.50
20	Devco	0.6	Blended	3.3	0.40	0.35	0.50
21	Devco	0.6	Blended	3.9	0.40	0.35	0.50

Test No.	Type of Coal	Firing Rate ($\times 10^6$Btu/hr)	Type of Limestone Feed	Ca/S Ratio	Air Distribution Fraction of Stoichiometric		
					Primary	Secondary	Tertiary
22	Minto	0.6	Burner Injection	1.6	0.40	0.35	0.50
23	Minto	0.6	Burner Injection	2.7	0.40	0.35	0.50
24	Minto	0.6	Burner Injection	3.5	0.40	0.35	0.50
25	Devco	0.6	Burner Injection	1.9	0.40	0.35	0.50
26	Devco	0.6	Burner Injection	2.8	0.40	0.35	0.50
27	Devco	0.6	Burner Injection	4.2	0.40	0.35	0.50
28	Devco	1.0	-	-	0.25	0.75	0.25
29	Minto	0.6	Blended	3.0	0.40	0.35	0.50
30	Devco	0.6	Blended	2.9	0.40	0.35	0.50
31	Minto	0.6	Downstream Injection	-	0.40	0.60	0.25
32	Minto	0.6	Downstream Injection	1.5	0.40	0.60	0.25
33	Minto	0.6	Downstream Injection	2.9	0.40	0.60	0.25
34	Minto	0.6	Downstream Injection	3.6	0.40	0.60	0.25
35	Devco	0.6	Downstream Injection	-	0.40	0.60	0.25

Test No.	Type of Coal	Firing Rate ($x10^6$Btu /hr)	Type of Limestone Feed	Ca/S Ratio	Air Distribution Fraction of Stoichiometric		
					Primary	Secondary	Tertiary
36	Devco	0.6	Downstream Injection	2.2	0.40	0.60	0.25
37	Devco	0.6	Downstream Injection	2.8	0.40	0.60	0.25
38	Devco	0.6	Downstream Injection	4.1	0.40	0.60	0.25

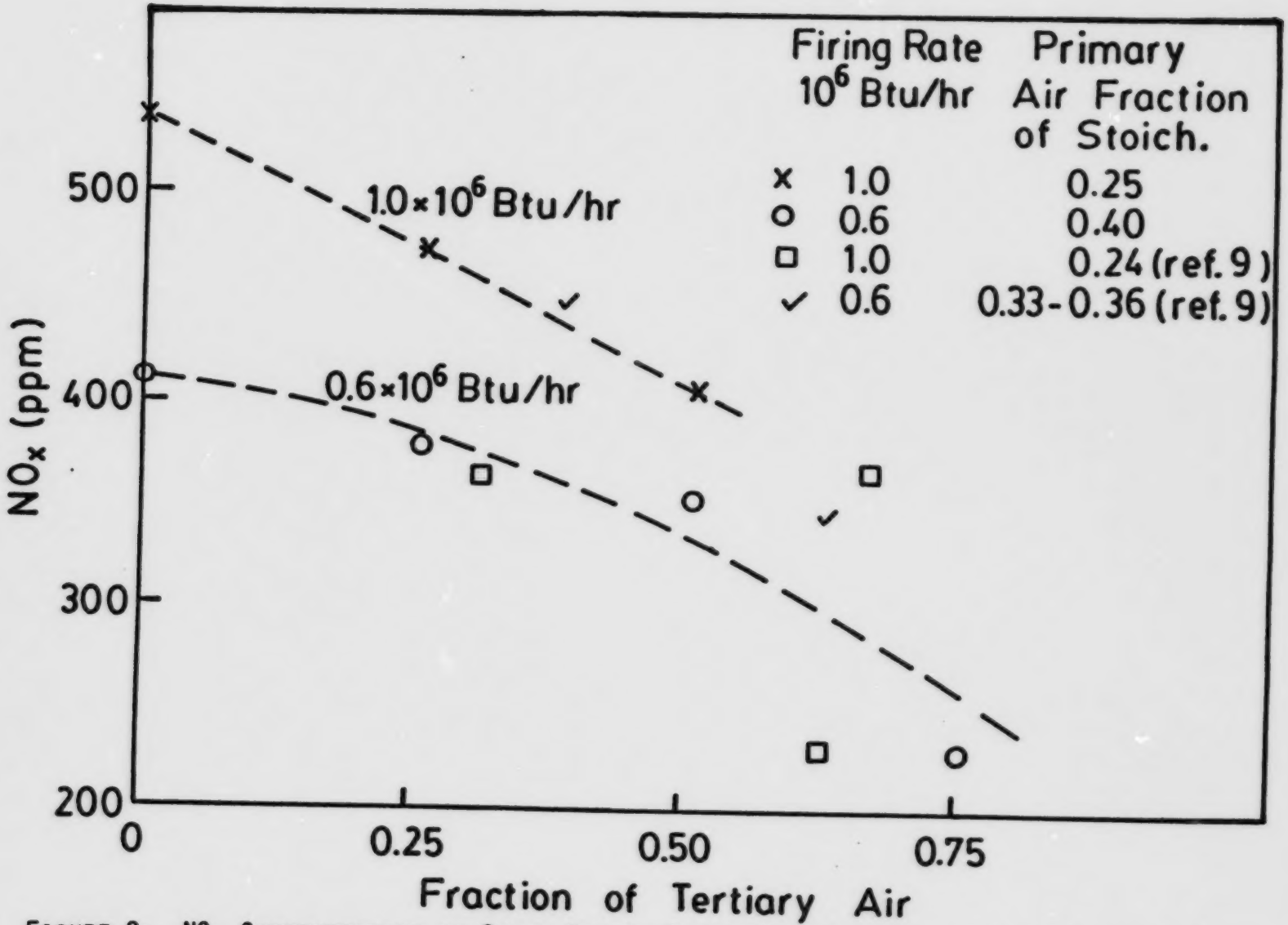


FIGURE 8: NO_x CONCENTRATION IN STACK GAS VS STOICHIOMETRIC FRACTION OF TERTIARY AIR MINTO COAL

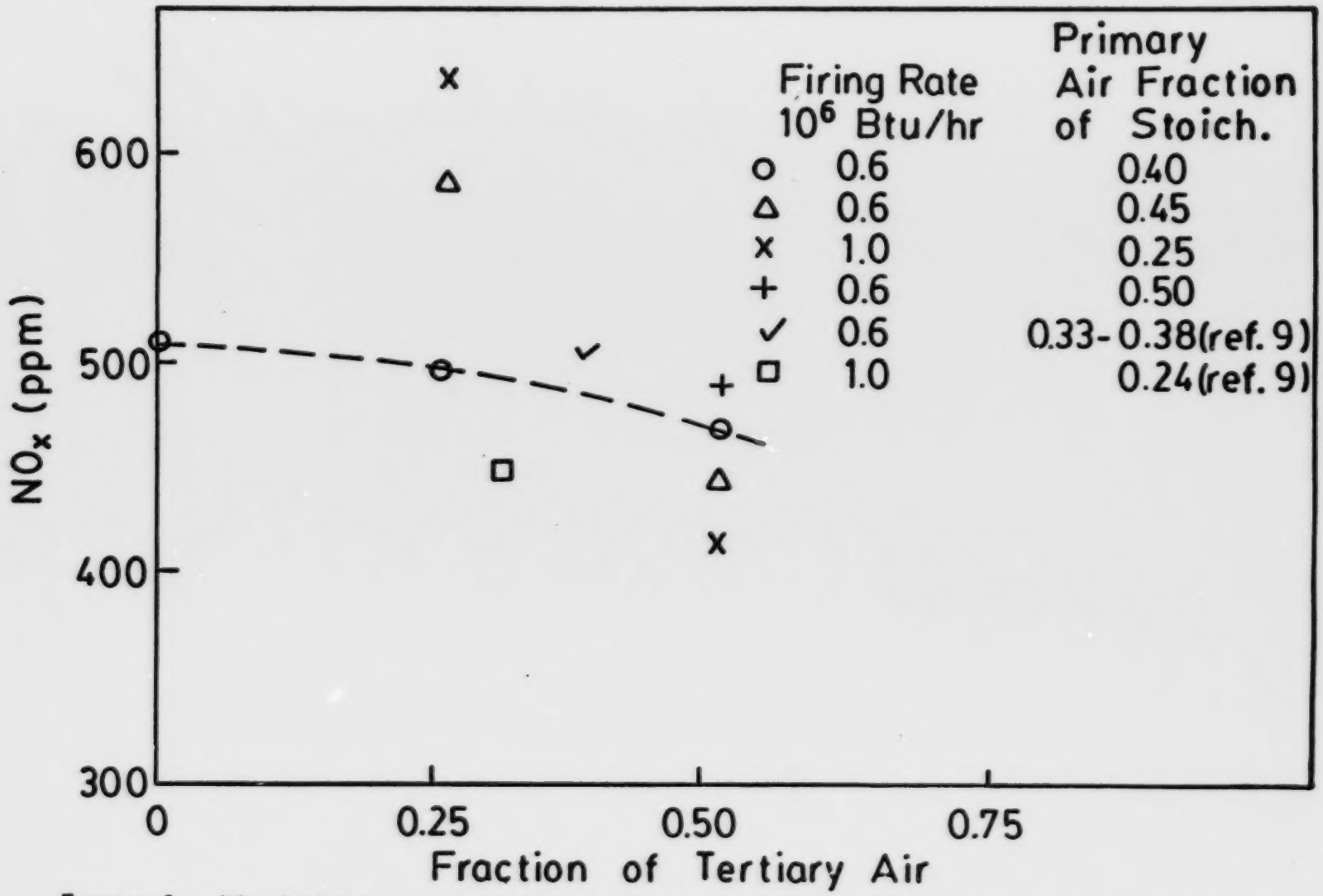


FIGURE 9: NO_x CONCENTRATION IN STACK GAS VS STOICHIOMETRIC FRACTION OF TERTIARY AIR DEVCO COAL

reduce SO_2 emissions. The subsequent tests involving the addition of limestone employed an air distribution of 40% primary air, 35% secondary air and 50% tertiary air to give a nominal excess air of 25%. Although results show that an air distribution with 75% tertiary air gives a lower NO_x concentration in the stack gas, this air distribution was not used since it caused firing difficulties and commercial units do not use such a high percentage tertiary air. All limestone addition tests were fired at the lower firing rate of 0.6 X 10^6 Btu/hr. The high firing rate of 1 X 10^6 Btu/hr was not extensively used since it caused problems with the operation of the furnace and the collection of the data when the insertion of probes into the furnace was required because of the significantly higher temperatures achieved.

The limestone was added to the furnace by blending with the coal, injection through the burner with tertiary air, or injection approximately 7 feet downstream of the burner. The air distribution for the downstream injection tests was changed to 40% primary air, 60% secondary air, and 25% tertiary air. This was done to maintain stoichiometric conditions at the burner.

Figures 10 and 11 indicate the concentration of SO_2 in the stack gas without the addition of limestone for Minto and Devco coals respectively versus the percentage of sulfur in the coal. These values are also compared with stoichiometric calculations based on the sulfur analysis of the coal, Appendix H.

Three different molar Ca/S ratios were tested for the effect on SO_2 emission, NO_x emission, gas exit temperature, and combustion efficiency. For the initial tests which involved the determination of the optimum air distribution for NO_x reduction, only port 7 was used for sampling. The gas sampling probe and solid sampling probe were used at the three insertion depths (refer to Figure 7), however, the suction pyrometer was not long enough to reach the third insertion depth. The sampling ports used for the limestone addition tests were 5, 6, and 7 at the three insertion depths. Appendix A presents the data generated from each port in every test.

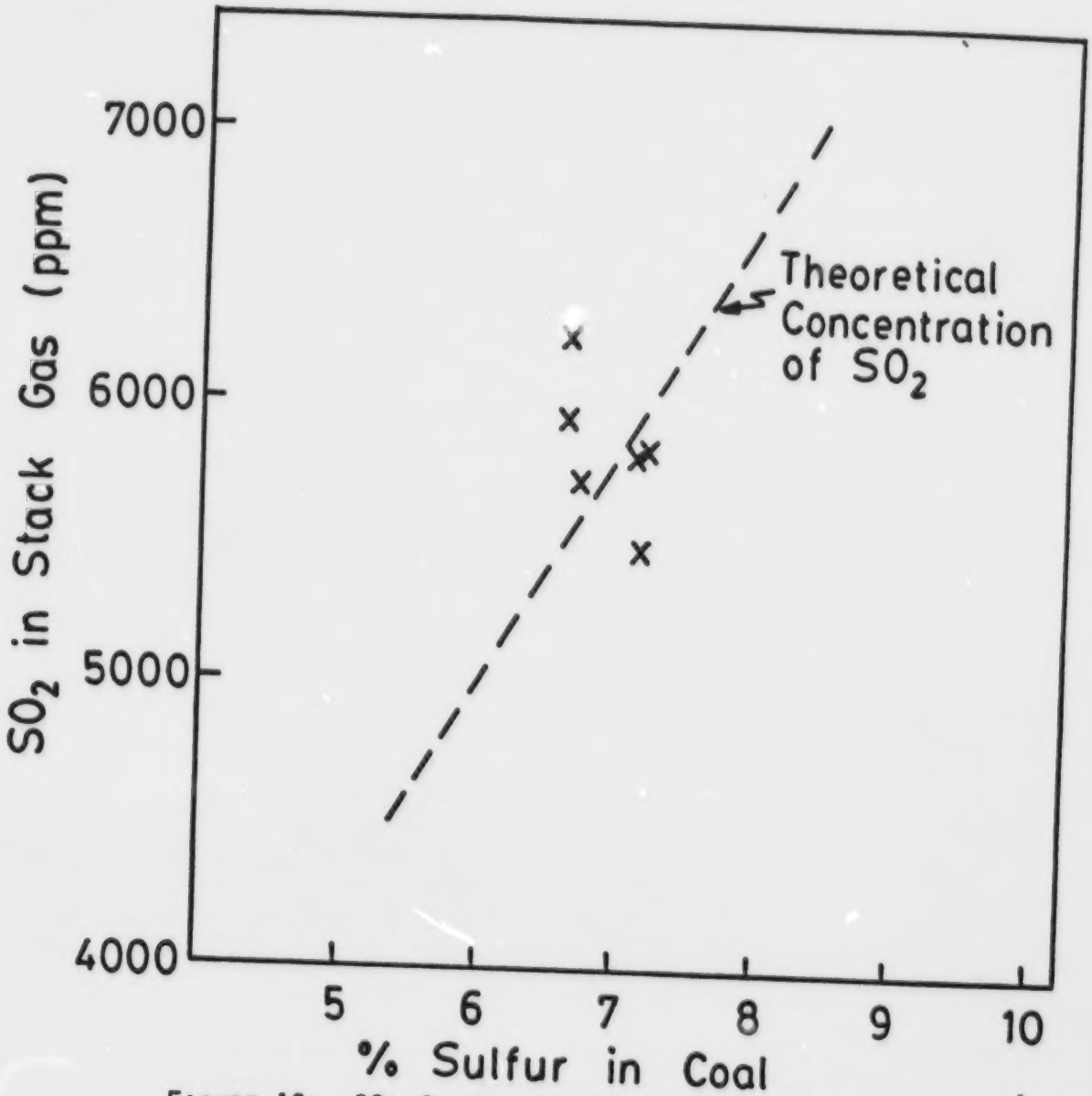


FIGURE 10: SO_2 CONCENTRATION IN STACK GAS VS % SULFUR IN COAL - MINTO COAL

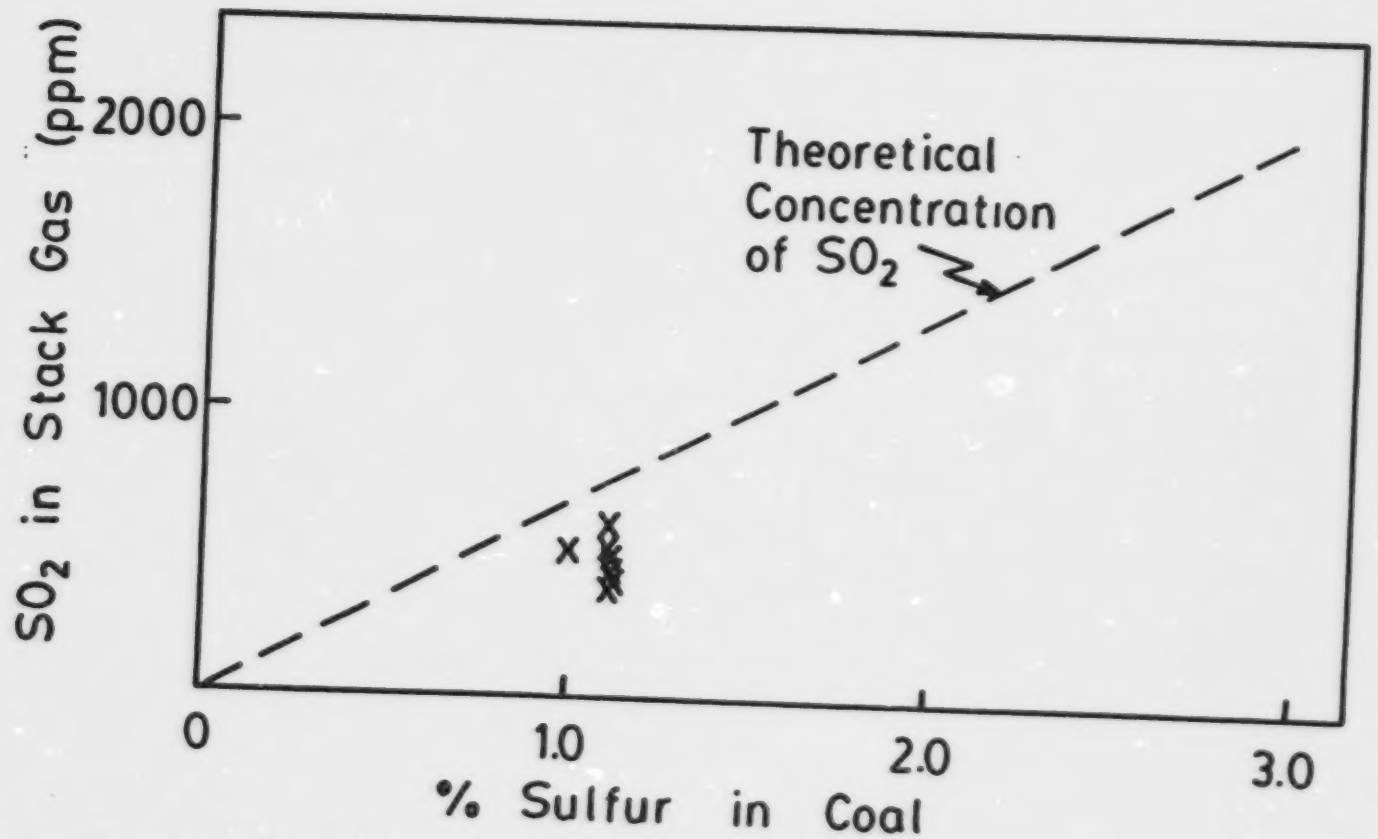


FIGURE 11: SO_2 CONCENTRATION IN STACK GAS VS % SULFUR IN COAL - DEVCO COAL

Figures 12 and 13 show the effect of limestone addition on SO_2 emission for Minto coal and Figures 14 and 15 show the effect of limestone addition on SO_2 emissions for Devco coal. The effect of the Ca/S ratio on NO_x emission and gas exit temperatures are shown in Figures 16 and 17 for Minto coal and Figures 18 and 19 for Devco coal. Tables 2 and 3 summarize the effect of limestone addition on SO_2 and NO_x emissions for Minto and Devco coals respectively.

Another way of considering the sulfur capture by the limestone is the calcium utilization with respect to sulfur capture. The percent Ca utilization for the tests runs for various Ca/S ratio for the three different limestone feed arrangements is presented in Table 4 for both Minto and Devco Coal.

The combustion efficiencies for all tests are summarized in Tables 5 and 6. These combustion efficiencies were determined from the analysis of the organic carbon in the solid samples collected at the furnace exit port as described in the sample calculation in Appendix D.

The solid samples collected at the furnace exit port were also analysed for unreacted $CaCO_3$. The % $CaCO_3$ in the solid sample and the % unreacted $CaCO_3$ determined by a material balance as shown in Appendix E are reported in Tables 7 and 8.

The percent sulfur capture for each test was determined using a gas side analysis or an ash analysis. There are three ash samples collected during a test, a solid sample from the furnace using the solid sampling probe, the fly ash from the bottom of the cyclone, and the bottom ash from the bottom of the furnace. The percent sulfur capture using the ash analyses was calculated by three methods:

Method 1: The sulfur capture calculation was performed based on a total ash balance using the analysis of the ash sample. From the sulfur analysis of the specific ash sample a sulfur capture for each ash sample was obtained, Appendix E.

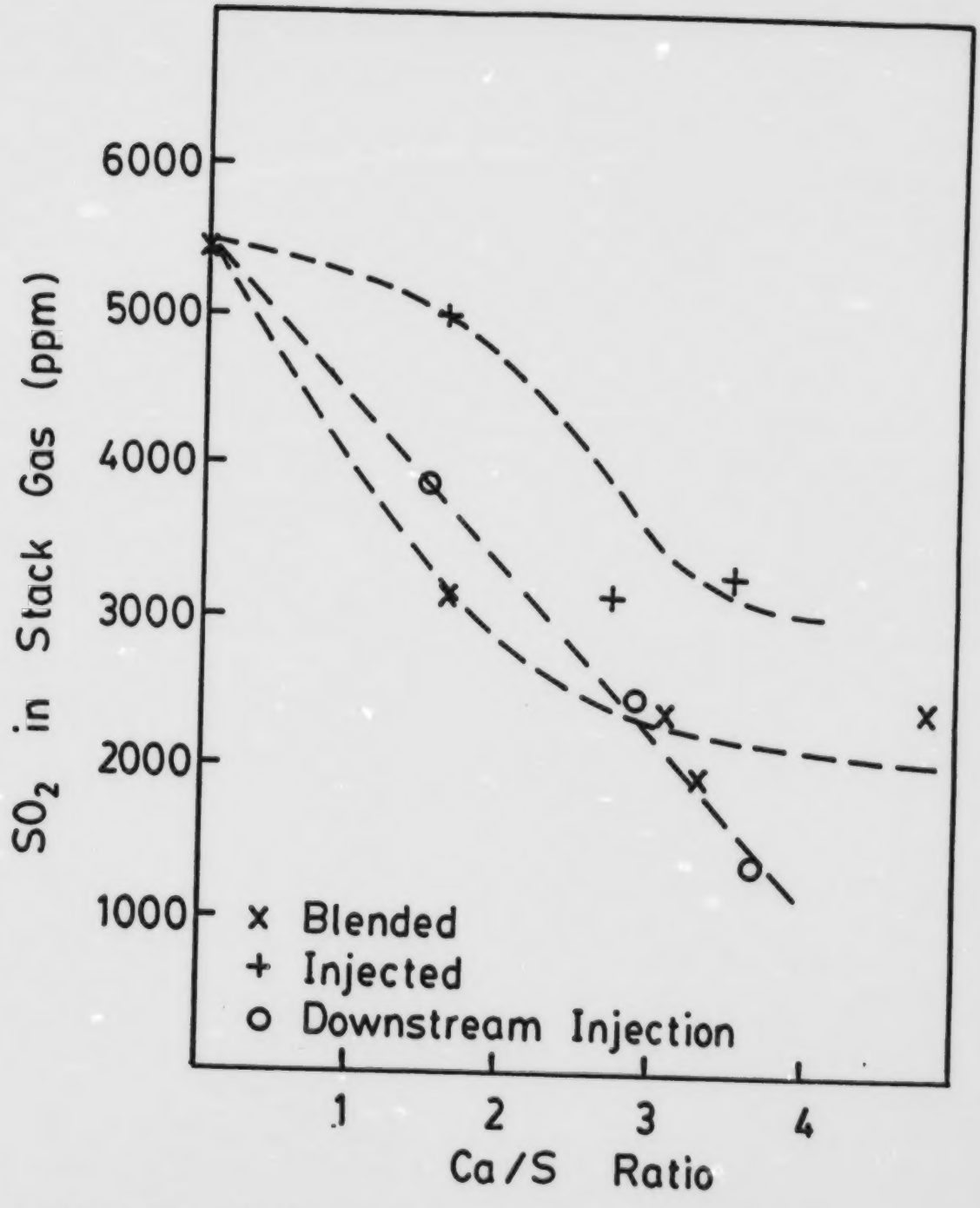


FIGURE 12: SO_2 CONCENTRATION IN STACK GAS VS CA/S RATIO
MINTO COAL

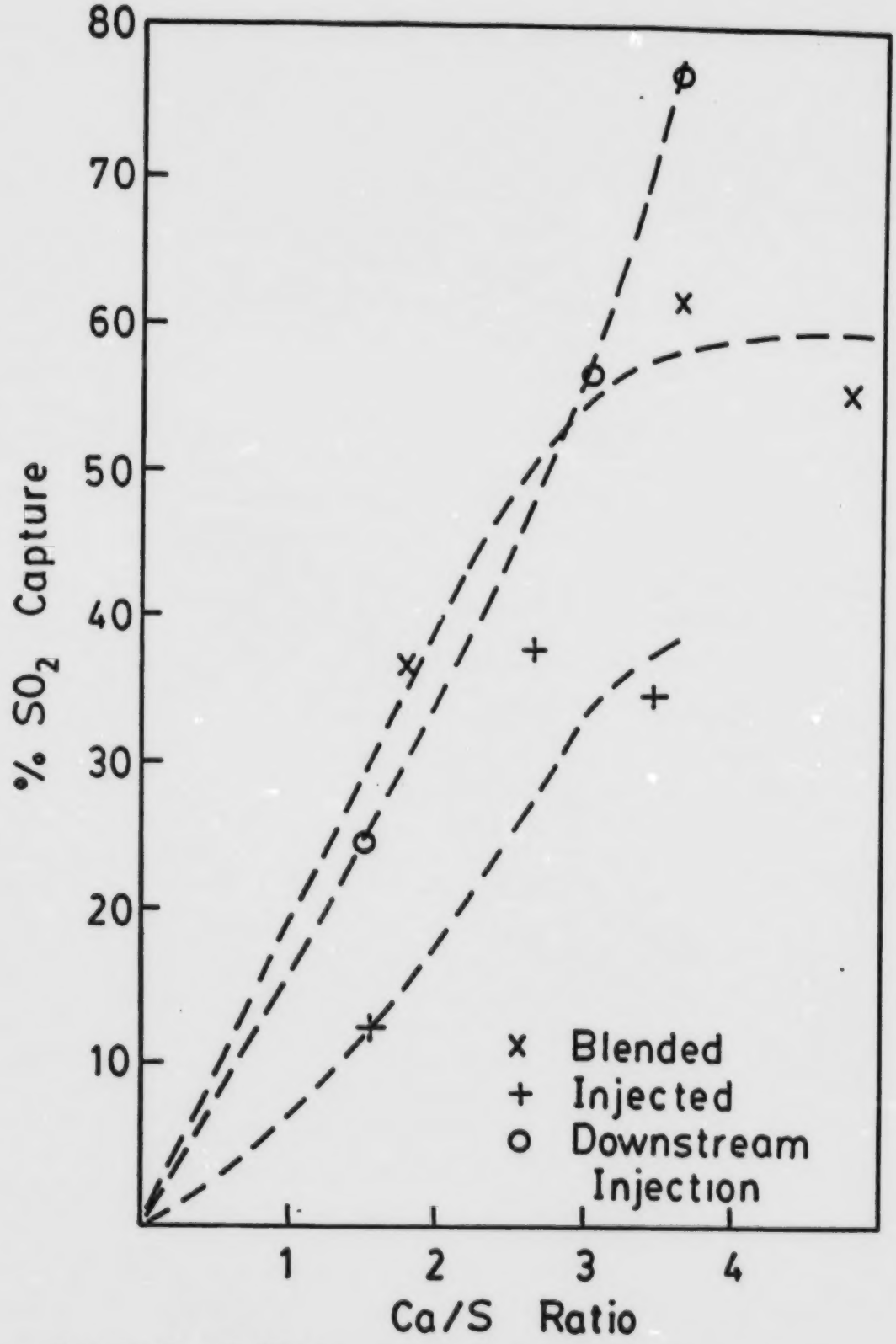


FIGURE 13: % SO_2 CAPTURE VS CA/S RATIO - MINTO COAL

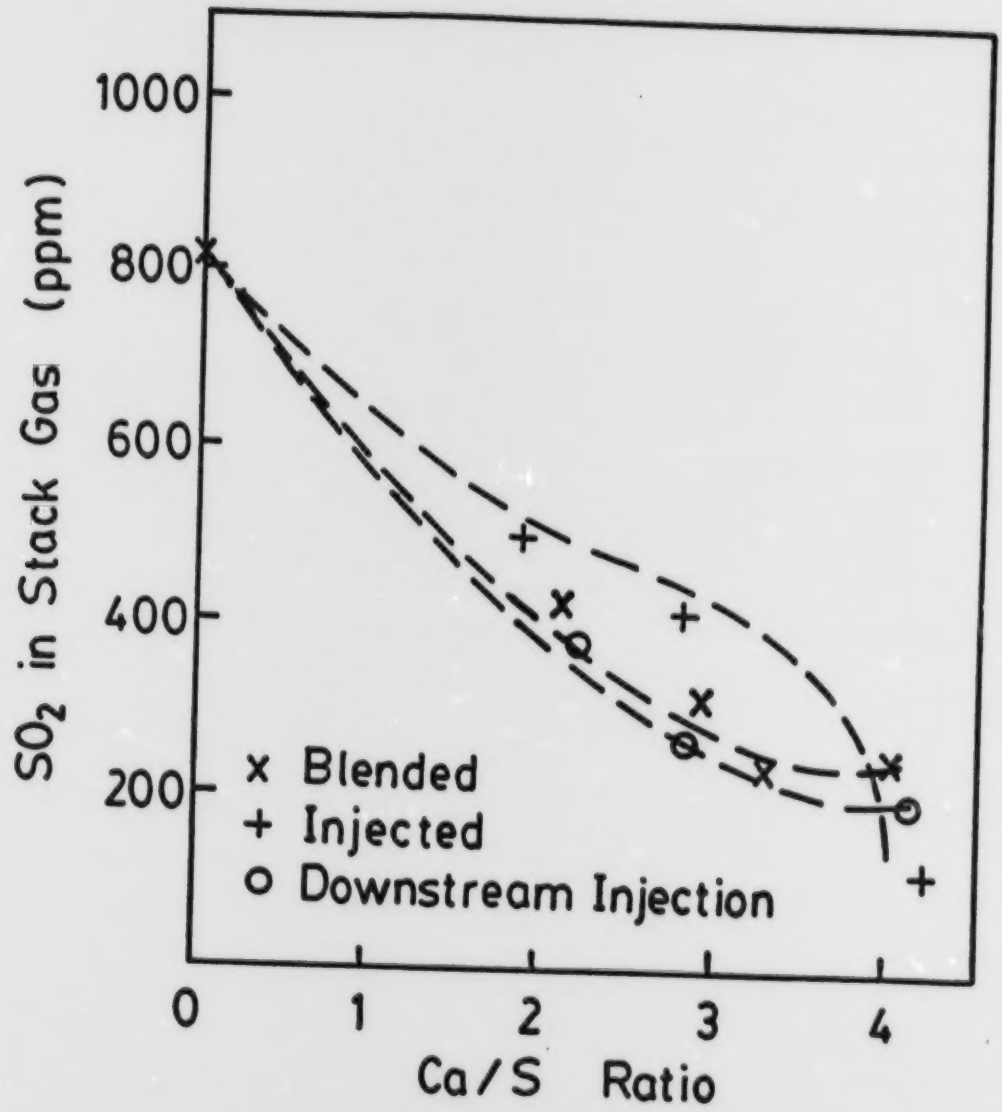


FIGURE 14: SO_2 CONCENTRATION IN STACK GAS VS CA/S RATIO
DEVCO COAL

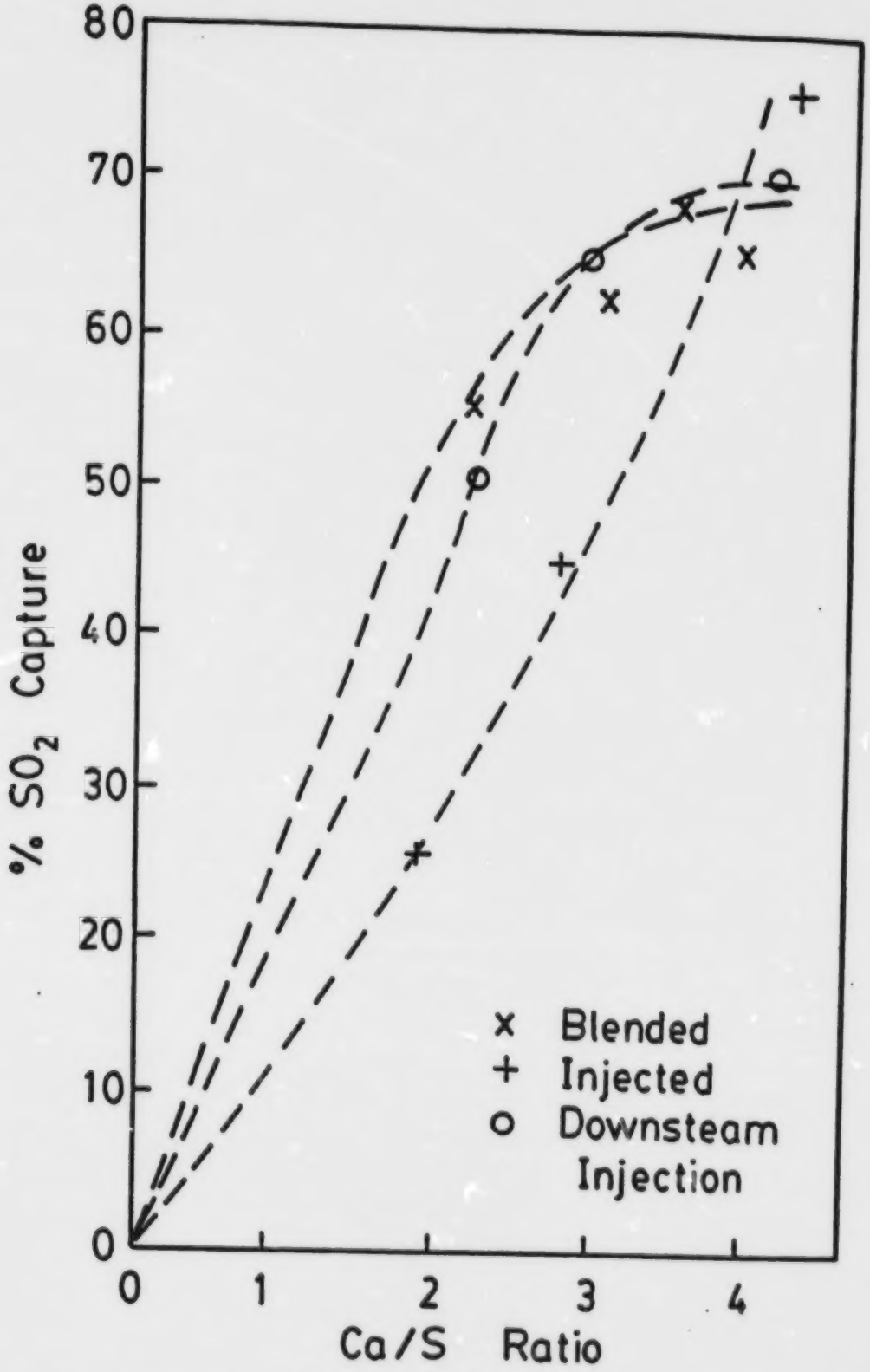


FIGURE 15: %SO_2 CAPTURE VS CA/S RATIO - DEVCO COAL

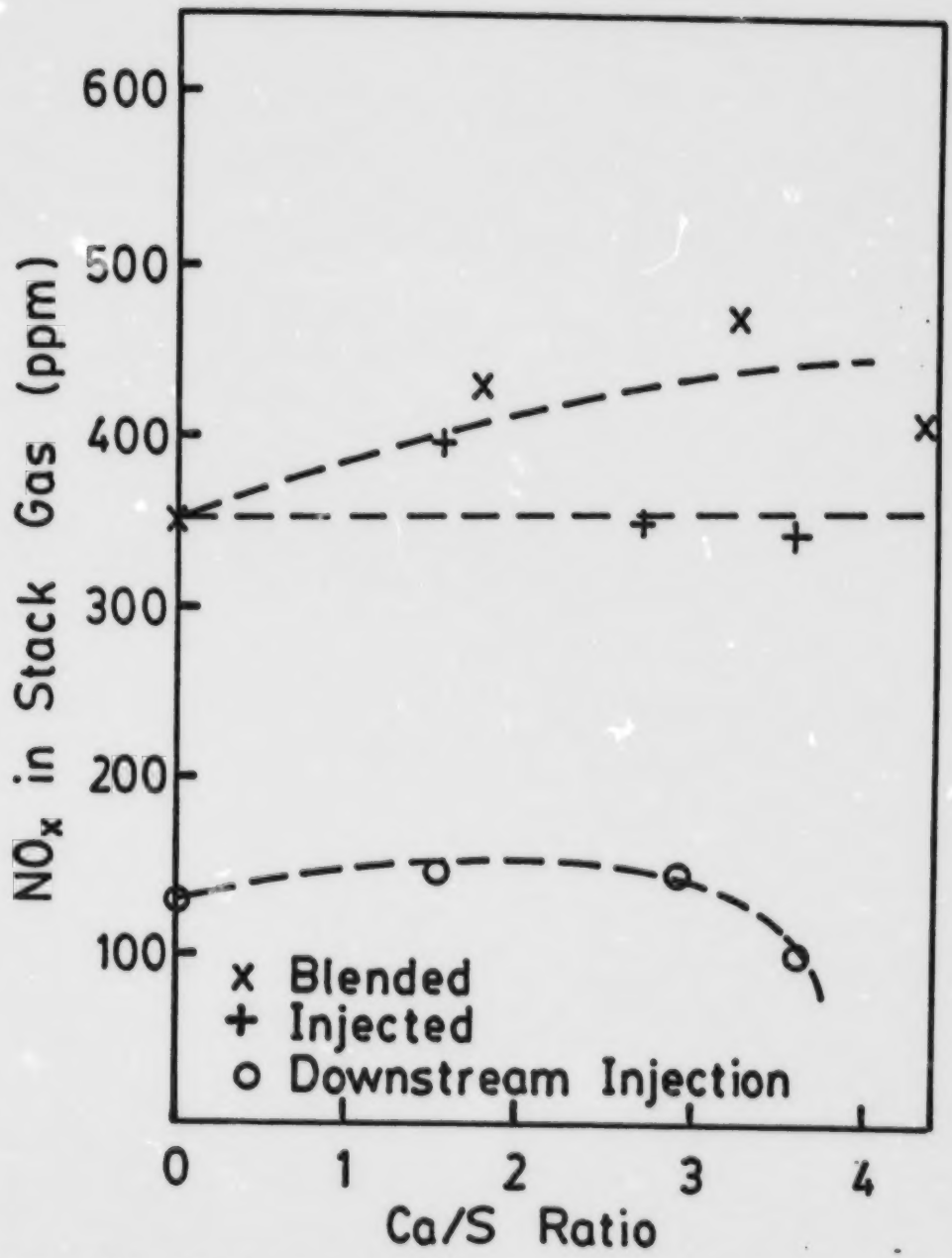


FIGURE 16: NO_x CONCENTRATION IN STACK GAS VS CA/S RATIO
- MINTO COAL -

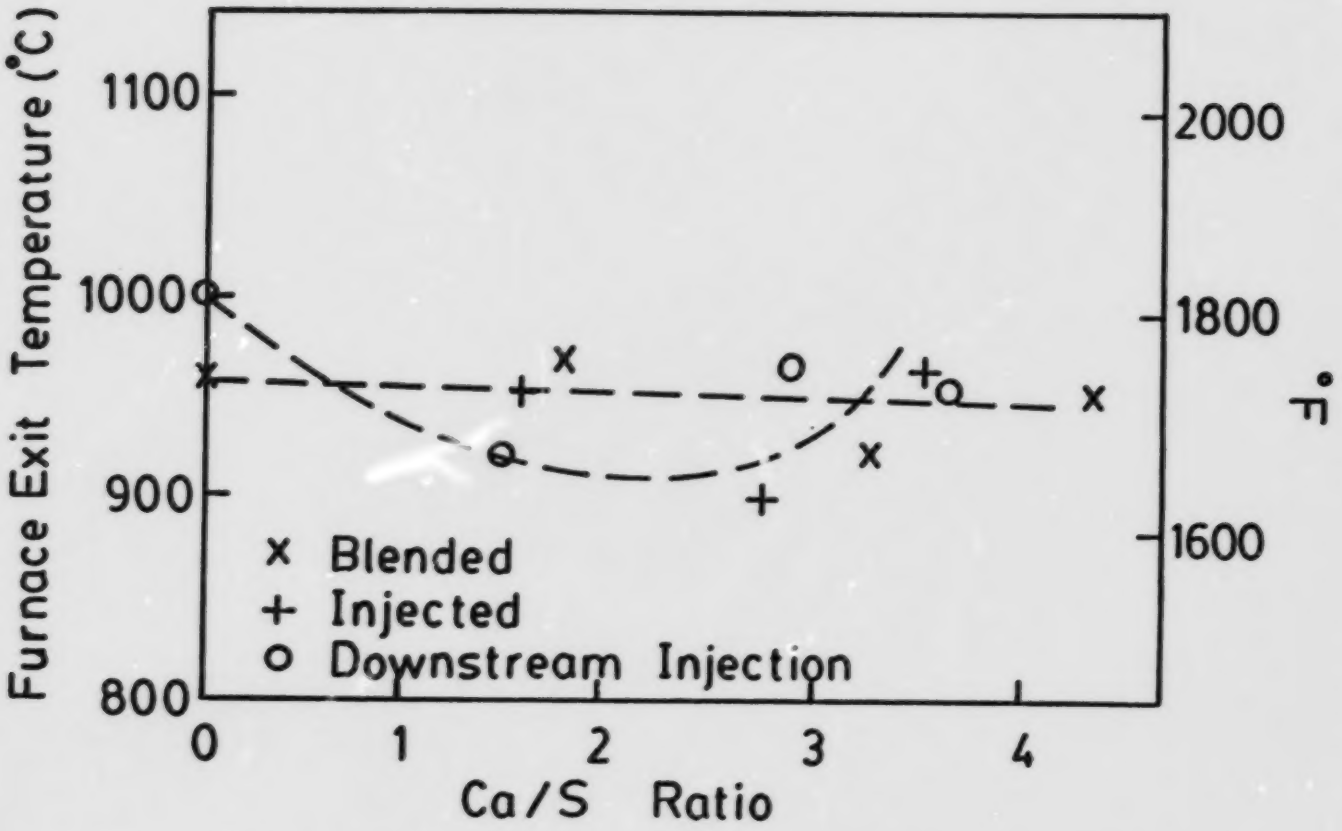


FIGURE 17: FURNACE EXIT TEMPERATURE VS CA/S RATIO - MINTO COAL

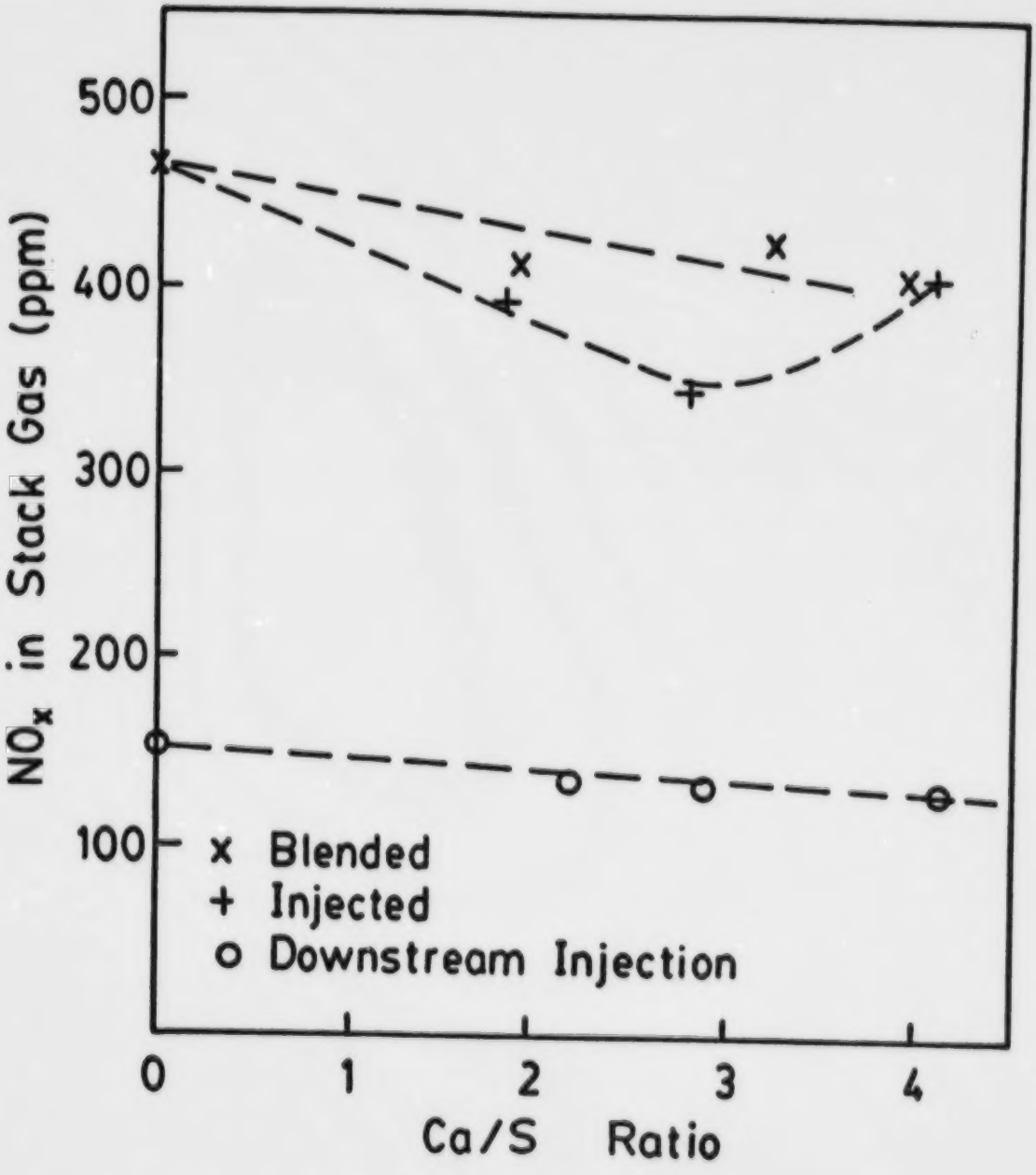


FIGURE 18: NO_X CONCENTRATION IN STACK GAS VS CA/S RATIO
- DEVCO COAL -

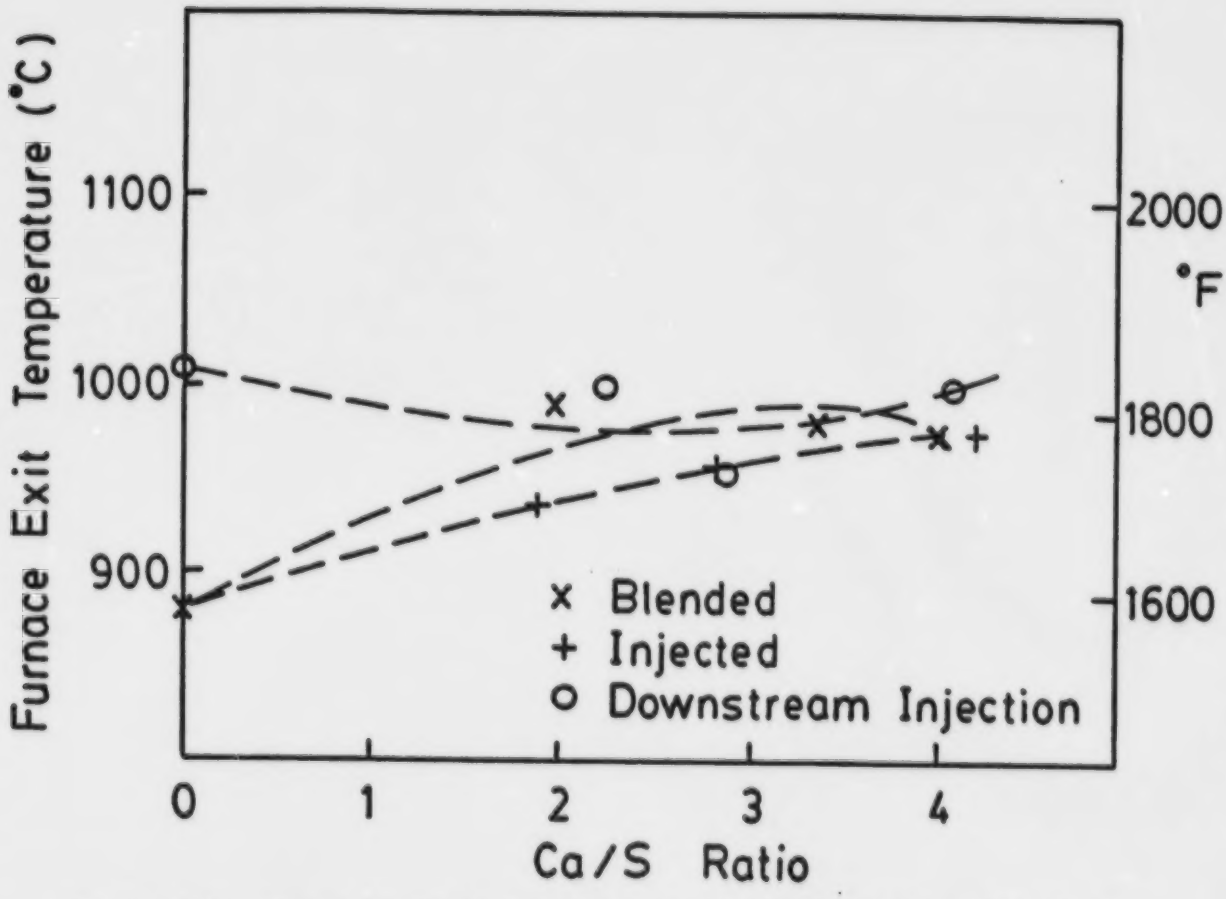


FIGURE 19: FURNACE EXIT TEMPERATURE VS CA/S RATIO - DEVCO COAL

Table 2 · Summary of Limestone Addition to Minto Coal

Type of Limestone Feed	Ca/S Ratio	SO_2 (ppm)	%Sulfur Removal	NO_x (ppm)
-	0	5697	-	367
Blended	1.8	3188	37.3	428
Blended	3.3	1830	62.5	469
Blended	4.8	2422	56.9	377
Injected	1.6	5002	12.7	394
Injected	2.7	3161	39.0	347
Injected	3.5	3310	35.7	342
Downstream Injection	1.5	3945	25.2	150
Downstream Injection	2.9	2459	57.3	148
Downstream Injection	3.6	1385	77.2	107

Table 3 Summary of Limestone Addition to Devco Coal

Type of Limestone Feed	Ca/S Ratio	SO_2 (ppm)	%Sulfur Removal	NO_x (ppm)
-	0	812	-	472
Blended	2.1	417	55.8	431
Blended	3.3	231	68.4	423
Blended	4.0	239	66.0	402
Injected	1.9	490	26.2	391
Injected	2.8	401	45.4	344
Injected	4.2	119	83.1	416
Downstream Injection	2.2	393	50.9	143
Downstream Injection	2.8	269	64.7	142
Downstream Injection	4.1	223	71.6	145

Table 4 Summary of Calcium Utilization for Limestone Addition

Coal	Type of Limestone Feed	Ca/S Ratio	% Ca Utilization
Minto	Blended	1.8	20.7
Minto	Blended	3.0	15.3
Minto	Blended	3.3	18.9
Minto	Blended	4.8	11.9
Minto	Burner Injected	1.6	7.9
Minto	Burner Injected	2.7	14.4
Minto	Burner Injected	3.5	10.2
Minto	Downstream Injected	1.5	16.8
Minto	Downstream Injected	2.9	19.6
Minto	Downstream Injected	3.6	21.4
		Minto average	15.7
Devco	Blended	2.1	26.6
Devco	Blended	2.9	20.8
Devco	Blended	3.3	20.7
Devco	Blended	4.0	20.0
Devco	Burner Injected	1.9	13.8
Devco	Burner Injected	2.8	16.2
Devco	Burner Injected	4.2	19.8
Devco	Downstream Injected	2.2	23.1

Coal	Type of Limestone Feed	Ca/S Ratio	% Ca Utilization
Devco	Downstream Injected	2.8	23.1
Devco	Downstream Injected	4.1	17.5
		Devco Average	20.1

Table 5 Combustion Efficiencies of Test Furnace for Various Operating Conditions

Type of Fuel	Type of Limestone Feed	Fraction of Tertiary Air for 1.25 Fraction Excess Air	Ca/S Ratio	%C in Ash	% Combustion Efficiency
Minto	-	0.75	-	2.7[illegible]	99.3
Minto	-	0.50	-	3.78	99.1
Minto	-	0.25	-	3.66	99.1
Minto	-	0	-	3.01	99.2
Devco	-	0.50	-	1.73	99.9
Devco	-	0.50	-	2.67	99.8
Devco	-	0.50	-	1.17	99.9
Devco	-	0.25	-	1.70	99.9
Devco	-	0.25	-	7.73	99.8
Minto	Blended	0.50	1.9	2.17	98.6
Minto	Blended	0.50	3.3	0.82	99.3
Minto	Blended	0.50	3.0	1.71	98.4
Minto	Blended	0.50	4.8	1.09	98.8
Devco	Blended	0.50	2.1	1.82	99.8
Devco	Blended	0.50	3.3	1.34	99.9
Devco	Blended	0.50	2.9	3.63	99.6
Devco	Blended	0.50	4.0	1.00	99.9
Minto	Injected	0.50	1.6	6.92	94.3
Minto	Injected	0.50	2.7	6.42	94.2
Minto	Injected	0.50	3.5	1.88	98.0
Devco	Injected	0.50	1.9	10.9	99.0
Devco	Injected	0.50	2.8	3.81	99.6
Devco	Injected	0.50	4.2	2.55	99.7

Table 6 Combustion Efficiencies of Test Furnace for Downstream Injection of Limestone Tests

Type of Fuel	Fraction of Tertiary Air for 1.25 Fraction Excess Air	Ca/S Ratio	%C in Ash	% Combustion Efficiency
Minto	0.25	-	7.1	98.4
Minto	0.25	1.5	4.7	96.2
Minto	0.25	2.9	3.5	96.2
Minto	0.25	3.6	1.5	98.1
Devco	0.25	-	12.4	99.7
Devco	0.25	2.2	11.6	98.7
Devco	0.25	2.8	5.2	99.4
Devco	0.25	4.1	5.6	99.0

Table 7 Unreacted Limestone for Blended Limestone/Coal Feed and Injected Limestone Feed

Type of Fuel	Type of Limestone Feed	Ca/S Ratio	%$CaCO_3$ in Ash	%$CaCO_3$ Unreacted
Minto	Blended	1.8	0.58	.67
Minto	Blended	3.3	1.08	1.08
Minto	Blended	4.8	1.67	1.55
Devco	Blended	2.1	9.83	11.82
Devco	Blended	3.3	6.91	6.90
Devco	Blended	4.0	2.00	1.69
Minto	Injected	1.6	1.17	1.50
Minto	Injected	2.7	2.92	2.99
Minto	Injected	3.5	1.33	1.22
Devco	Injected	1.9	4.08	5.13
Devco	Injected	2.8	5.75	5.55
Devco	Injected	4.2	10.16	8.99

Table 8 Unreacted Limestone for Downstream Injection of Limestone

Type of Fuel	Ca/S Ratio	%$CaCO_3$ in Ash	%$CaCo_3$ Unreacted
Minto	1.5	13.9	17.5
Minto	2.9	9.7	10.3
Minto	3.6	6.3	6.2
Devco	2.2	0.50	0.59
Devco	2.8	19.2	19.9
Devco	4.1	30.5	31.0

Method 2: By determination of the Ca/S ratio in each ash sample a sulfur capture calculation was performed by comparison of the Ca/S ratio entering the furnace with the Ca/S ratio in the ash sample, Appendix F.

Method 3: The fly ash and bottom ash flows were determined from Ca and Fe balances and with the sulfur analysis of each of these ash streams an overall sulfur capture was calculated, Appendix G.

The percent sulfur captures using each ash analysis method for all the limestone addition tests are summarized in Table 9. This table also shows the percent sulfur capture calculated by doing a sulfur balance using the gas analysis for each test.

In order to determine the reliability of results two tests were repeated to verify data reproducibility. These results are shown in Table 10.

Figure 20 shows the relationship between equilibrium NO_x formation and gas temperature. This figure includes the data for NO_x concentration versus gas temperature for both Minto and Devco coal with or without the addition of limestone. The short lines on this diagram give the range of NO_x formation based on fuel nitrogen only for the two coals.

The theoretical flame temperature for each Ca/S ratio versus heat removal rate for Minto coal is shown in Figure 21. Figure 22 indicates the theoretical flame temperature versus heat removal rate for Devco coal, Appendix I. Also included in this figure are the flame temperatures for the different Ca/S ratios. In both cases it was assumed that all $CaCO_3$ was converted to CaO. One calculation is presented on Figure 21 for 50% removal of sulfur for a Ca/S ratio of 2.0.

Table 9 Summary of Sulfur Captures for Limestone Addition to Minto and Devco Coal

Type of Coal	Type of Limestone Feed	Ca/S Ratio	Ash Sample	%S Capture Solid Side (Method 1)	%S Capture Solid Side (Method 2)	%S Capture Solid Side (Method 3)	%S Capture Gas Side
Minto	Blended	1.8	Solid Sample	19.9	22.7	27.4	37.3
			Fly Ash	17.1	18.4		
			Bottom Ash	44.2	44.0		
Minto	Blended	3.3	Solid Sample	37.4	47.4	39.5	62.5
			Fly ash	32.3	35.0		
			Bottom Ash	53.5	66.5		
Minto	Blended	3.0	Solid Sample	31.5	35.2	35.2	59.7
			Fly Ash	29.0	26.8		
			Bottom Ash	60.9	70.6		
Minto	Blended	4.8	Solid Sample	49.0	63.7	51.6	56.9
			Fly Ash	44.1	51.7		
			Bottom Ash	83.8	92.8		
Devco	Blended	2.1	Solid Sample	32.8	44.8	32.7	55.8
			Fly Ash	31.5	29.7		
			Bottom Ash	54.3	50.0		
Devco	Blended	3.3	Solid Sample	19.4	23.1	38.5	68.4
			Fly Ash	33.1	30.6		
			Bottom Ash	52.7	61.0		
Devco	Blended	2.9	Solid Sample	40.4	39.4	43.8	60.4
			Fly Ash	33.0	26.9		
			Bottom Ash	66.9	68.7		
Devco	Blended	3.9	Solid Sample	13.4	17.7	60.9	66.0
			Fly Ash	33.6	29.3		
			Bottom Ash	68.2	81.9		
Minto	Injected	1.6	Solid Sample	21.1	24.0	32.5	12.7
			Fly Ash	19.2	18.2		
			Bottom Ash	47.5	46.5		

(Table 9 Continued)

Type of Coal	Type of Limestone Feed	Ca/S Ratio	Ash Sample	%S Capture Solid Side (Method 1)	%S Capture Solid Side (Method 2)	%S Capture Solid Side (Method 3)	%S Capture Gas Side
Minto	Injected	2.7	Solid Sample	22.6	27.2	16.6	38.9
			Fly Ash	22.8	14.8		
			Bottom Ash	24.6	65.7		
Minto	Injected	3.5	Solid Sample	40.7	47.6	29.6	35.7
			Fly Ash	27.0	23.6		
			Bottom Ash	59.0	42.3		
Devco	Injected	1.9	Solid Sample	26.2	30.5	19.1	26.2
			Fly Ash	24.1	17.4		
			Bottom Ash	59.0	69.3		
Devco	Injected	2.8	Solid Sample	24.9	22.4	34.7	45.4
			Fly Ash	23.9	26.2		
			Bottom Ash	43.1	50.9		
Devco	Injected	4.2	Solid Sample	14.7	14.7	-	83.1
			Fly Ash	13.8	14.5		
			Bottom Ash	26.7	34.4		
Minto	Downstream Injection	1.5	Solid Sample	28.9	24.4	14.0	25.2
			Fly Ash	32.6	24.2		
			Bottom Ash	39.0	31.3		
Minto	Downstream Injection	2.9	Solid Sample	41.8	51.0	45.1	57.3
			Fly Ash	39.3	45.9		
			Bottom Ash	42.8	53.4		
Minto	Downstream Injection	3.6	Solid Sample	50.2	59.9	58.6	77.2
			Fly Ash	53.5	52.9		
			Bottom Ash	51.9	65.5		
Devco	Downstream Injection	2.2	Solid Sample	22.3	27.8	36.7	50.9
			Fly Ash	21.0	22.9		
			Bottom Ash	41.7	47.8		
Devco	Downstream Injection	2.8	Solid Sample	27.9	26.9	38.4	64.7
			Fly Ash	30.5	26.7		
			Bottom Ash	52.2	65.1		
Devco	Downstream Injection	4.1	Solid Sample	35.7	31.3	52.7	71.6
			Fly Ash	35.4	29.9		
			Bottom Ash	74.6	93.2		

Table 10 Comparative Tests

Type of Coal	Ca/S Ratio	%S Capture Gas Side	%S Capture			NO_X Conc'n (ppm)	Exit Temp (°C)
			Solids Sample	Fly Ash	Bottom Ash		
Minto (Blended)	3.3	62.5	37.4	32.3	53.5	371.4	942
Minto (Blended)	3.0	59.7	31.5	29.0	60.9	369.0	958
Devco (Blended)	3.3	68.4	19.4	33.1	52.7	423.5	1005
Devco (Blended)	2.9	60.4	40.4	33.0	66.9	324.6	977

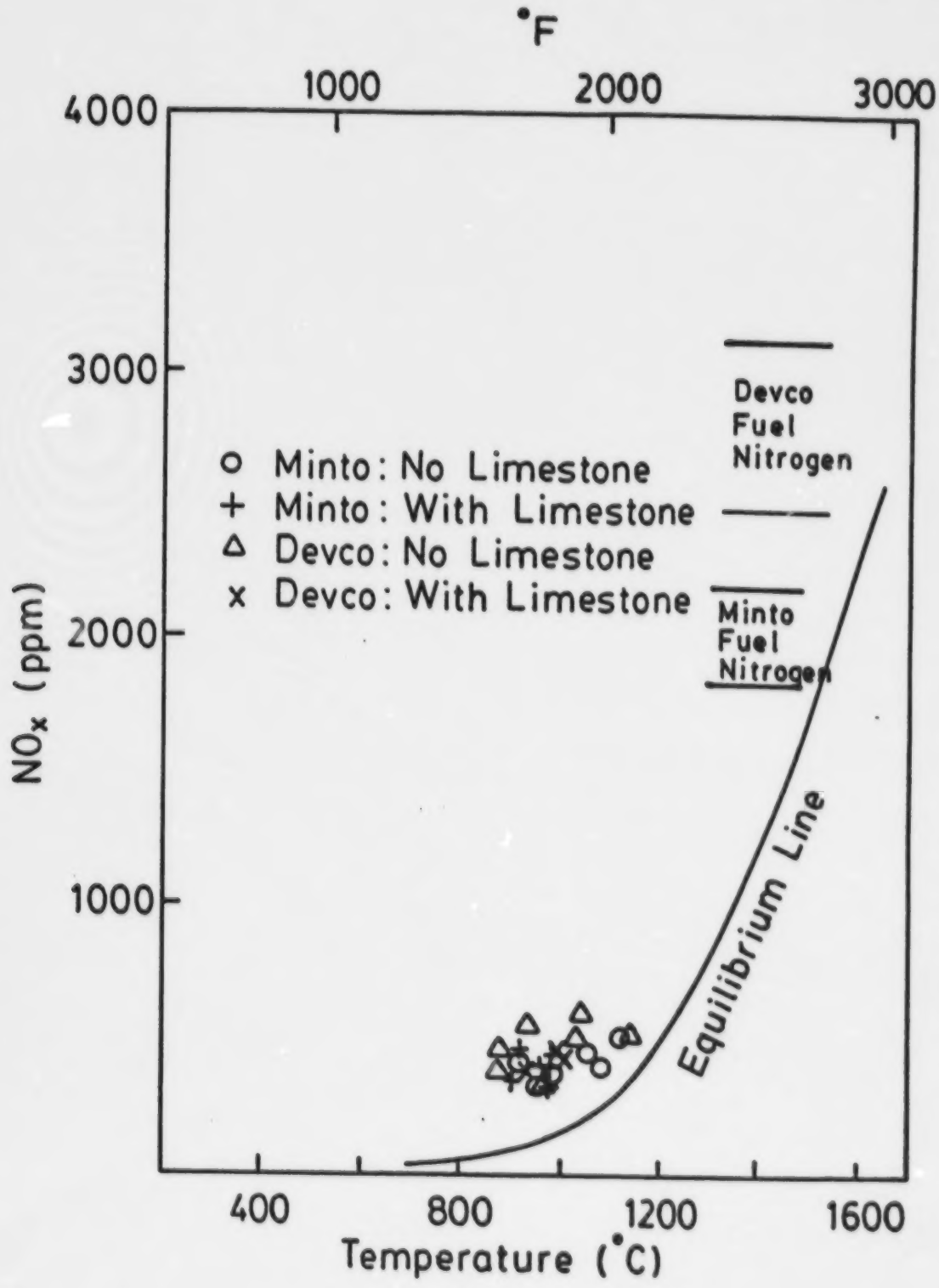


FIGURE 20: EQUILIBRIUM NO_x CONCENTRATION VS TEMPERATURE FOR MINTO AND DEVCO COAL WITH 25% EXCESS AIR

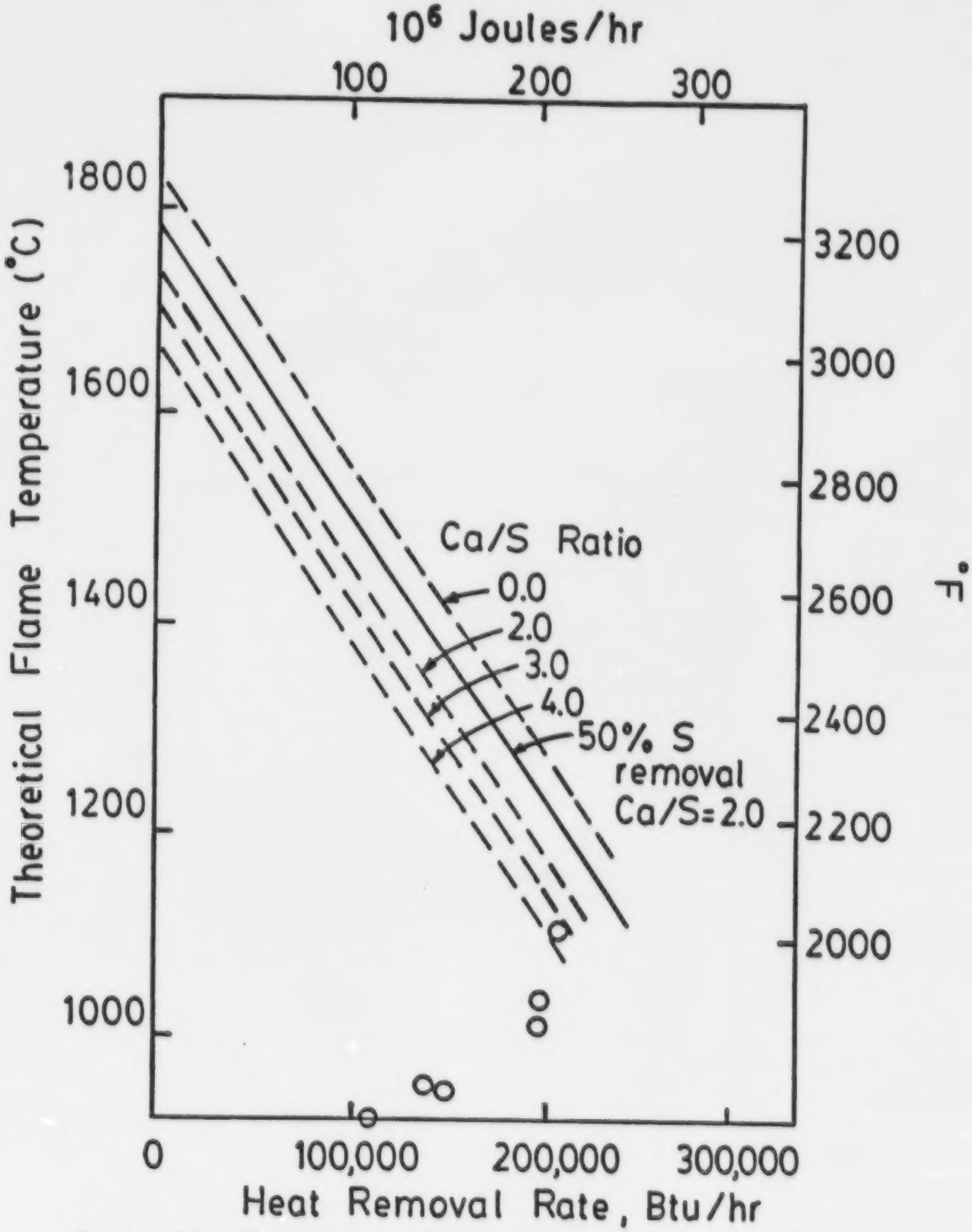


FIGURE 21: THEORETICAL FLAME TEMPERATURE VS HEAT REMOVAL RATE FOR MINTO COAL WITH 25% EXCESS AIR FOR VARIOUS CA/S RATIO

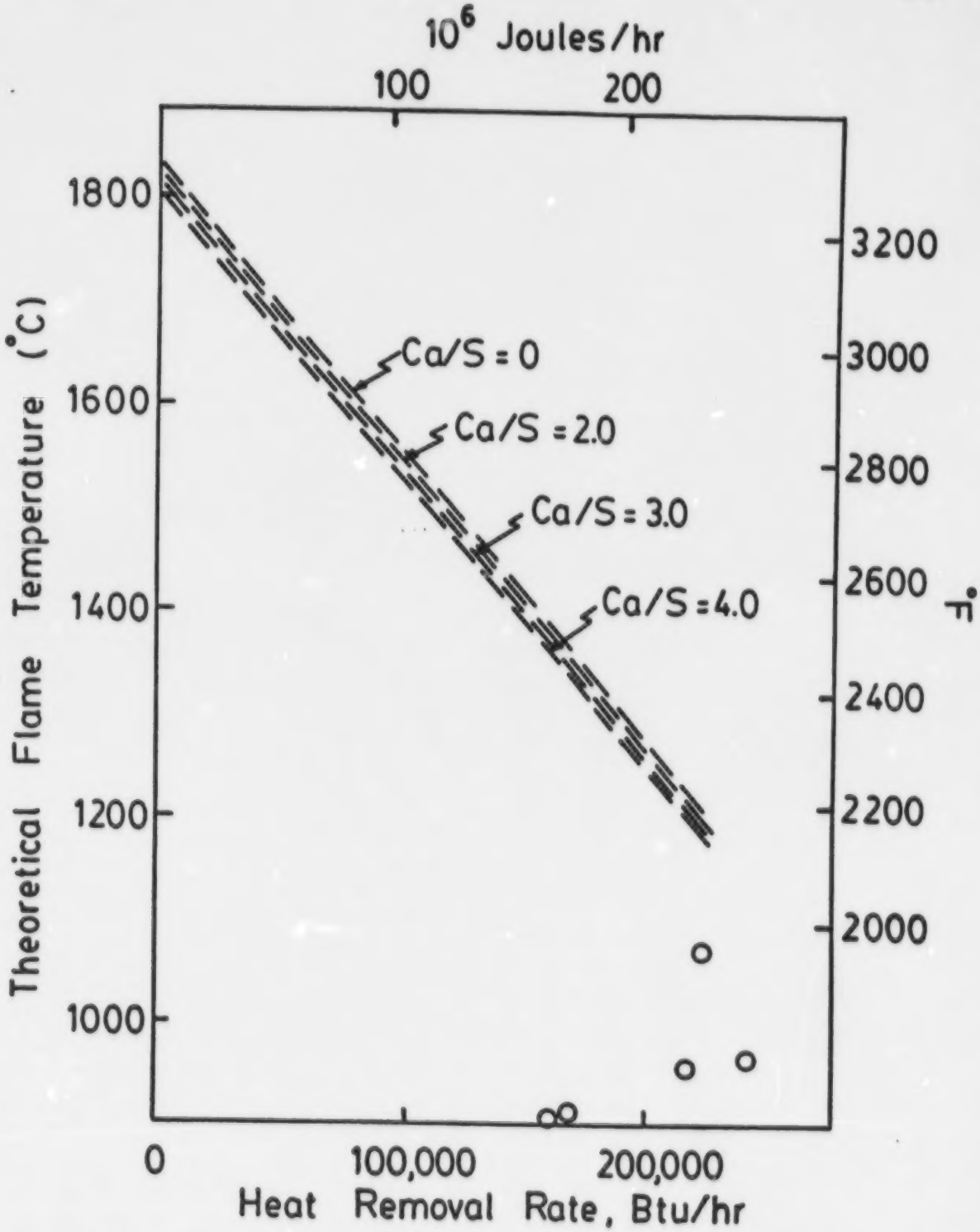


FIGURE 22: THEORETICAL FLAME TEMPERATURE VS HEAT REMOVAL RATE FOR DEVCO COAL WITH 25% EXCESS AIR FOR VARIOUS CA/S RATIOS

V Discussion

1.0 NO_x Concentration in Stack Gas

The formation of NO_x during coal combustion is derived from two sources, fuel nitrogen and nitrogen from the air. The nitrogen within the fuel will form fuel NO_x when the nitrogen is oxidized. The formation of fuel NO_x is heavily dependent on the oxygen concentration in the combustion region as well as the nitrogen and oxygen content of the fuel.

The other source of NO_x is from the oxidation of the molecular nitrogen contained in the combustion air. NO_x formed in this way is termed thermal NO_x. Thermal NO_x formation is affected by flame temperature and oxygen concentration with thermal NO_x increasing as flame temperature and oxygen content increase.

With the Low NO_x burner a certain amount of the combustion air is introduced to the burner at a later stage of the flame development thus creating a reducing zone at the center of the flame and lowering the peak flame temperature. This technique is known as staged combustion and has been proven to reduce NO_x emissions from coal combustion (2, 5, 9).

As Figures 8 and 9 indicate for both coals used in this project as the amount of tertiary air increases the NO_x concentration decreases. There are four tertiary air lines which enter the furnace radially just below the burner. Therefore diverting the air to the tertiary air line is staging the combustion air to some extent. Figure 8 shows that NO_x concentration is reduced when firing from a low to a high staging air distribution for Minto coal at a firing rate of 1.0 X 10^6 Btu/hr and 0.6 X 10^6 Btu/hr. Figure 9 shows the same trend for Devco coal although there is increased scatter in the data. NO_x concentrations for Minto coal were reduced from 410 ppm to 250 ppm at the lower firing rate and from 550 ppm to 400 ppm at the high firing rate. For Devco coal NO_x concentrations were reduced

from 500 ppm to 450 ppm at the low firing rate and from over 600 ppm to 400 ppm at the high firing rate.

In later runs when the tertiary air was fed 7 feet down the furnace from the burner the NO_x concentration in the stack gas decreased substantially for both coals, to 150 ppm in the case of Minto coal and to 143 ppm for Devco coal, Figures 16 and 18 and Tables 2 and 3. These trends in NO_x reduction with staged air firing are consistent with industrial practice. (5).

As well as diverting combustion air to the tertiary line the fraction of combustion air entering the burner between the primary and secondary air lines were varied. Figure 9 indicates that a lower primary air fraction may affect the NO_x concentration with less primary air showing lower NO_x concentration. However the major factor in reducing NO_x concentration was the amount of air diverted to the tertiary air line. This result was reinforced in later testing when the tertiary air line was moved further downstream of the burner, approximately 7 feet, where NO_x concentrations between 100 and 200 ppm were achieved.

Also included in Figures 8 and 9 are NO_x concentrations observed for different tertiary air fractions reported by Pierrynoswki (9). Pierrynowski carried out similar tests on NO_x and SO_2 reduction with the same furnace used in this project. Generally Pierrynowski reports higher NO_x concentrations for the low firing rate of Minto coal than the high firing rate of Minto coal, whereas this project observed the opposite trend higher NO_x concentrations for the higher firing rate of Minto coal. The NO_x concentrations reported for Devco coal by Pierrynowski and this project are essentially similar as indicated in Figure 9.

As indicated in Figures 8 and 9 the NO_x concentrations for the same firing rate are higher for Devco coal compared to Minto coal. This is presumably due to the higher per cent nitrogen in Devco coal, 1.60 - 2.00 %, compared to Minto coal, .98 - 1.17 %.

As Figures 16 and 18 indicate the addition of limestone to the furnace had in general little effect on the concentration of NO_x. The blended tests with Minto coal showed an increase of approximately 25% in NO_x concentration with increasing Ca/S ratio but the downstream injection tests with Minto coal had a decrease of about 23% in NO_x concentration. The burner injected tests with Minto coal had virtually no change in NO_x concentration with increasing Ca/S ratio. With Devco coal only the burner injected tests had any significant change in NO_x concentration with increasing Ca/S ratio.

The furnace exit temperature did not change as the Ca/S ratio increased for the blended and burner injected tests of Minto coal as Figure 17 indicates. The down stream injection test with no limestone added showed a higher gas exit temperature than either the blended or injected tests but with the addition of limestone the temperature fell slightly and was similar to those of the other tests. With Devco coal, as seen in Figure 19, the gas exit temperature of the downstream injection test without limestone was also higher than the blended and burner injected tests but the temperature then fell with the addition of limestone to within the same range as the blended and burner injected tests. For both Minto and Devco coal the furnace exit temperature varied between 880°C and 1010°C.

The temperature measurements indicate that the flame temperature is not sufficiently altered by limestone addition to affect the NO_x formation and thus concentration in the stack gas. In general NO_x forms at high temperatures and the concentration is not reduced by a subsequent lower temperature as may be suggested by equilibrium considerations, Figure 20. The equilibrium "freezes" at about 1200°C and the NO_x remains at this level as the gases are cooled. It is only useful to reduce oxygen concentration at high temperatures to reduce NO_x formation. The endothermic reaction of the limestone calcination is not large enough to reduce the flame temperature by more than 170°C for Minto coal and 30°C for Devco coal. This does not seem to be of sufficient magnitude to reduce NO_x formation.

2.0 SO_2 Concentration in Stack Gas

The sulfur present in coal will oxidize to form sulfur dioxide during combustion. When limestone is added to the furnace the calcium carbonate in the limestone will first calcine to calcium oxide which is then capable of reacting with the sulfur dioxide in the gas to create calcium sulfate thus reducing the SO_2 concentration in the flue gas.

Studies by Borgwardt (1) indicate that when limestone particles traverse through temperatures in excess of 1200°C sintering of the limestone particles occur and the reactive surface area greatly decreases. If limestone is blended with coal, when fired the limestone passes through the flame where temperatures considerably in excess of 1200°C occur. With Low NO_x burner technology it is possible to avoid the addition of limestone through the flame by injecting the limestone in the outer tertiary air flow or even at a significantly greater distance downstream from the burner.

This project consisted of adding the limestone by three methods, blended with the coal, injection at the burner with tertiary air, and downstream injection with tertiary air. For both Minto and Devco coals three Ca/S ratios were tested, nominally 2:1, 3:1, and 4:1. In general the blended fuel tests show better sulfur capture than the burner injected tests based on gas analyses as Figures 13 and 15 indicate. The blended fuel tests also show slightly higher sulfur capture over the downstream injection tests. The downstream injection tests, however, show higher sulfur capture than the burner injected tests.

Previous workers (3, 6, 9) have found that downstream injection of limestone gives higher SO_2 removal than burner injected limestone which is consistant with the results presented here. Even the reduction in residence time by approximately 1/2 is presumably overcome by the superior reactivity of the limestone not exposed to the high temperature calcination.

These same workers (3, 6, 9) also found that blended coal and limestone firing gave lower SO_2 removal than downstream limestone injection. The results from this study gave similar SO_2 removal by these two methods of limestone addition. This result is difficult to explain particularly when compared with the tests in which limestone was injected with the tertiary air at the burner which gave lower SO_2 removal than coal and limestone blended firing. A possible explanation is a higher residence time for blended compared to downstream injection and better mixing of limestone for blended compared to burner injected limestone. These two effects combined could make the overall reactivity of the limestone for the blended firing and the the downstream injection similar.

This study showed that burner injected limestone with the tertiary air gave lower SO_2 removal than blended coal-limestone firing for both coals. An earlier study (7) on a pilot scale furnace found approximately similar SO_2 removal for these two types of firing with a low NO_x burner. The results of this earlier study gave considerably lower overall SO_2 removal than this study. However the temperature of the gases leaving this pilot scale furnace were considerably higher than those measured in the present study giving a short time exposure to a temperature in which the limestone is reactive.

The maximum sulfur capture for Minto coal was 77.2% for a downstream injection test with a Ca/S ratio of 3.6. This was the only test which showed a higher sulfur capture than a blended test with an equivalent Ca/S ratio. The Devco coal tests showed a maximum sulfur capture of 83.1% for a burner injected test with a Ca/S ratio of 4.2. The downstream injection test with a Ca/S ratio of 4.1 also showed a higher sulfur capture than the blended test with a Ca/S ratio of 4.0. However the blended tests showed higher sulfur capture at the lower Ca/S ratios than either of the injected tests. In general the sulfur capture increased with increasing Ca/S ratio.

The high SO_2 removal from the stack gas achieved within this test furnace can be attributed to the high residence time within the furnace, approximately 4.4 seconds at a firing rate of 0.6 X 10^6 Btu/hr. When the limestone was injected downstream with the tertiary air the residence time of the particles would be approximately one half this value or 2.2 seconds. The high SO_2 removal with a Ca/S ratio of between 3 and 4 are in agreement with previous work for similarly high residence times (6, 9).

The residence time of the combustion gas within the temperature range of limestone reactivity, 1300 - 800 °C, in a typical pulverized coal fire boiler is less than one second. Therefore one cannot expect such high SO_2 removed with limestone injection for an industrial boiler as has been demonstrated (5) where SO_2 removal was between 40 and 50% for similar Ca/S ratios.

This level of removal within an industrial fired boiler is satisfactory for low sulfur coals with present environmental regulations, but not sufficient for high sulfur coals which are indigenous to Eastern Canada.

3.0 SO_2 Adsorption Based on Analyses of Solid Samples

The per cent sulfur absorbed by the limestone presented in Figures 13 and 15 for Minto and Devco coal respectively are based on the SO_2 measurement made on a sample of stack gas taken at the exit of the furnace.

As indicated previously for each test solid samples were taken at the furnace exit with a solids sampling probe, "solids sample" from the solids collections bin at the bottom of the furnace, "bottom ash" and from the bin below the cyclone, "fly ash". Each of these samples were analysed for sulfur, calcium, unreacted calcium carbonate, organic carbon and iron. As explained previously the sulfur capture based on these analyses was calculated by three methods.

For a particular sample it would be reasonable to expect Method 1 and Method 2 to agree with each other for a particular solid sample. While there are some variations this is generally the case for nearly all samples with an occasional exception, Minto injected Ca/S = 2.7, bottom ash.

Since it would be reasonable to expect different proportions of calcined limestone and coal ash to be deposited as bottom ash and fly ash, Method 1 and Method 2 are theoretically suspect for calculation of sulfur adsorption by either of these methods. However, since the solid sample is taken directly from the gas stream in the furnace, either of these methods would be theoretically reasonable to determine the sulfur capture from the solids analysis for such a sample.

Method 3 accounts for the relative amounts of coal ash and calcined limestone being deposited in the two ash bins. Therefore this method is theoretically preferred for the analyses of both bottom ash and fly ash and is the value reported under Method 3 in Table 8.

Based on the above discussion of methods of solids analysis the top figure in each block are the theoretically preferred values for percent sulfur capture in Table 9. These values should be compared with the percent sulfur capture based on the analysis of the stack gas given in the same Table 9.

While the trends are similar in that the % sulfur capture by each method increases with an increase in the Ca/S ratio there is not good agreement between the numbers for a particular test in all cases. In general the gas side percent sulfur capture is higher than the percent sulfur capture based on solids analyses. In some tests there is reasonably good agreement among all values, in other tests there is a wide dispersion of values.

Since the gas side sulfur capture is based on the analysis of the SO_2 in the stack gas and the analyzer was recalibrated before each test run it is believed that this is the most reliable result.

Therefore, all comparisons and discussions within this report use the % sulfur capture based on the stack gas analysis. Of course % sulfur capture values depend on the analysis of the coal.

As a general principle one would expect difficulty in obtaining a highly reliable material balance based on solids analyses without reliable flow measurements of the solid streams themselves. Such flow measurements were not attempted in these tests. The bottom ash and fly ash samples were taken from bins which were emptied before each test. However, there is always the problem of obtaining a "representative" sample of such a solid stream. Furnace slag from previous runs can contaminate the solid samples. Furthermore not all of the leaving solid particles were collected in the bottom and fly ash bins because the heat exchanger located downstream of the cyclone frequently plugged up with particles and had to be cleaned. The collection efficiency of cyclones is normally low for particles less than 20 μm and it is thus possible that a significant fraction of the leaving solids may have escaped the cyclone. It is thus unlikely that the bottom ash and fly ash samples were representative of the leaving solid stream.

Due to the high sulfur captures being reported two tests were repeated to confirm data reproducibility. The two tests that were repeated were Minto and Devco coal blended with limestone at a Ca/S ratio of 3.0. Table 8 presents the results of these tests and compares them with the results of the earlier tests. The Ca/S ratio of the repeat test for Minto coal decreased from 3.3 to 3.0 which resulted in a 4.5 % decrease in sulfur capture based on gas side analysis. The sulfur capture based on the solid sample analysis decreased by 15%, the NO_x concentration decreased by 1% and the furnace exit temperature increased by 2%. These changes are relatively small and can be explained by the reduced Ca/S ratio.

The Devco blended test showed a decrease in Ca/S ratio from 3.3 to 2.9 for the repeat test which resulted in a 11% decrease in sulfur capture based on the gas side analysis. The sulfur capture based on the solid sample analysis for the repeat test increased considerably due to the questionable low sulfur capture reported for the first test. The NO_x concentration for the repeat Devco test dropped by 23% and the furnace exit temperature dropped by 3%. These comparative tests confirm that the high sulfur captures reported for this test furnace are valid.

4.0 Calcium Utilization in Limestone

Another way of looking at sulfur capture by the limestone is the calcium utilization of the limestone. The per cent calcium utilization for various Ca/S ratios for the various types of limestone feed arrangements and both Minto and Devco coals is presented in Table 4.

The major observation with respect to per cent calcium utilization is that it is remarkably similar for most of the runs for a particular coal. For Devco coal it is particularly uniform where it varies from a minimum of 13.8 % to a maximum of 26.6 % and is usually within ±4% of 20%. For Minto coal there is somewhat more variation with a minimum of 7.9 % and a maximum of 21.4% but again the value is usually within ±5% of 16%.

The percent calcium utilization is significantly higher, for the low sulfur Devco coal, average 20.1%, as compared to 15.7 % for the high sulfur Minto coal.

These numbers indicate that the calcium utilization is similar for increasing Ca/S ratio over the ranges studied. This presumably means that a higher Ca/S ratio could remove additional SO_2 by an amount which is proportional to the additional calcium added. This would of course give even higher per cent sulfur removal than achieved in these tests.

5.0 Combustion Efficiency

The combustion efficiency for each test was calculated from the amount of unburned carbon present in the solid sample taken from the bottom access port of the furnace. The combustion efficiency of the tests for NO_x reduction, where no limestone was added, are all above 99% as seen in Table 5. With the addition of limestone the majority of tests remain between 98 and 100%. However the combustion efficiency for a Ca/S ratio of 2 and 3 burner injected tests with Minto coal fall to 94.3% and 94.2% respectively. Tests with a Ca/S ratio of 2 and 3 for downstream injection tests with Minto coal also fall below 98% to 96.2% efficiencies.

Downstream injection of limestone would tend to lower combustion efficiencies since only a stoichiometric amount of air was provided at the burner. Since the ultimate analysis of the coal varied somewhat from test to test this could slip to a value of less than stoichiometric air at the burner.

The two low combustion efficiencies for burner injected limestone with Minto coal remain unexplained.

6.0 Unreacted Limestone

As indicated in Tables 6 and 7 some of the limestone remained unreacted in all solid samples collected with the solid sampling probe.

The downstream injected tests for both Minto and Devco coal gave high values of unreacted $CaCO_3$ in the solid sample except for one test. This can be explained by the shorter residence time in the furnace approximately 2.2 seconds vs 4.4 seconds for burner injection or blended. Also the limestone in downstream injected tests was subjected to a lower temperature history which would reduce the rate of calcination of the limestone particles.

The variation of unreacted limestone with changing Ca/S ratio was less clear. For three test series Minto blended, Devco burner injected and Devco downstream injected the % unreacted $CaCO_3$ increased with an increase in Ca/S ratio. For two test series, Devco blended and Minto downstream injected the % unreacted $CaCO_3$ decreased with an increase in Ca/S ratio. For one case Minto burner injected it increased and then decreased with an increase in Ca/S ratio. This information would seem to be rather inconclusive with respect to the effect of Ca/S ratio on unreacted limestone. However, all values of unreacted limestone were less than 10% except one Devco, burner injected, Ca/S = 4.2, unreacted limestone = 10.16%. It is important to note, however, that even with the long residence time of this test furnace, 4.4 seconds, some limestone remains uncalcined.

7.0 Furnace Exit Temperatures

Furnace exit temperatures are given in Figures 17 and 19 for various Ca/S ratios for Minto and Devco coal firing respectively. All values fall within the range of 980 - 1010 °C. The furnace exit temperature was not affected significantly by the Ca/S ratio.

As indicated in Figure 20, the equilibrium value for NO_x increases rapidly with increasing temperature above 1200°C. The formation of NO from N_2 and O_2 is an endothermic reaction and thus the equilibrium value of NO increases with temperature.

Figures 21 and 22 present the theoretical temperature of the combustion of Minto and Devco coal as a function of heat removal rate and Ca/S ratio for a firing rate of 600,000 Btu/hr. The data indicates that the furnace lost considerably more heat than that removed by the cooling water alone.

Limestone addition does lower the theoretical temperature of the flame and furnace significantly at a particular heat removal rate for Minto coal firing. However, the reaction of lime with sulfur dioxide and oxygen is exothermic and therefore this reaction would raise the furnace temperature above the values presented for a

particular Ca/S ratio depending on the amount of sulfur adsorption. This effect would be 32°C for a Ca/S ratio of 2 with 50% SO_2 capture as shown in Figure 21.

Limestone addition does not lower the theoretical temperature of the flame and furnace significantly at a particular heat removal rate for Devco coal firing for the Ca/S ratios used. This is due to the low value of sulfur, approximately 1%, in this coal and therefore the relatively low flow rates of limestone.

Since the furnace exit temperature for the firing of both coals did not change significantly with Ca/S ratio the NO_x concentration in the furnace exit gas did not vary significantly with Ca/S ratio for burner injected or blended limestone feed. As indicated previously it increased from 350 - 400 for Minto blended and remained unchanged for Minto burner injected. It decreased from 460 to 400 for both Devco blended and Devco burner injected.

8.0 Other Gas Concentration Measurements

Throughout all the tests gas concentration measurements of CO_2, O_2 and CO were made.

The measurement of CO_2 and O_2 was carried out primarily as a check for the appropriate combustion air in firing the furnace. All test runs were carried out with a nominal excess air of 25% based on a typical analyses of the two coals fired.

The CO_2 and O_2 at the furnace exit remained similar throughout the test program. The CO_2 ranged between 12.56 - 17.04 % and the O_2 ranged between 2.51 - 5.10 %. The CO_2 values were in general somewhat higher for limestone addition to the high sulfur Minto coal but remained essentially the same for the low sulfur Devco coal. This agrees with the difference in limestone flow for similar Ca/S ratios.

The CO measured in the furnace exit gas varied over a wide range from zero to 2105 ppm However, in most runs the value was less than 600 ppm.

The values of CO_2 and O_2 were measured at three positions across the furnace exit. In general there was difference of approximately 1 % in the CO_2 and O_2 values from one side of the furnace to the other. The CO_2 concentration was higher on the side of the furnace away from the access port and the O_2 concentration was lower on this same side. This condition was consistent throughout the entire test program.

VI Conclusions

1. NO_x formation was reduced by 50% or more for a high staging of air feed compared to burner air feed.

2. The generation of NO_x under similar firing conditions for the high nitrogen coal, Devco, was greater than for the low nitrogen coal, Minto.

3. A sulfur capture of greater than 60% was achieved with a Ca/S ratio of 3.5 - 4.0 for both the high level and low level sulfur coals. A sulfur capture of approximately 50% was achieved with a Ca/S ratio of 2.5 - 3.0 for both the high level and low level sulfur coals.

4. The sulfur capture for limestone addition by blended firing and downstream injection was higher than limestone addition by burner injection.

5. The calcium utilization of the injected limestone was, on the average, better for the low sulfur coal, Devco, 20.1% than the high sulfur coal, Minto, 15.7 %. The per cent calcium utilization did not vary consistantly with Ca/S ratio for either coal.

6. The low NO_x burner was capable of maintaining low NO_x emissions in the presence of limestone addition for Ca/S ratios of up to 4.0 for both high sulfur coal, Minto, 7 % and low sulfur coal, Devco 1 %.

VII References

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Appendix A

Test Data

Test No. : 1 Date: May 18, 1989

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/ hr

Flowrates:

Primary Air: 40 scfm
Secondary Air: 10 scfm
Tertiary Air: 76 scfm
Coal : 1.14 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.52	13.62	224	5985	239	1005.7
7-2	2.84	14.24	532	6187	210	1016.5
7-3	2.14	16.58	610	6361	229	-

%Carbon in Solid Sample = 2.76

Combustion Efficiency = 99.3%

Heat Removal Rate = -

Test No. : 2 Date: May 24, 1989

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/ hr

Flowrates:

Primary Air: 40 scfm
Secondary Air: 60 scfm
Tertiary Air: 25 scfm
Coal : 1.15 lb/min

Gas Concentration and Temperature Profile:

Port# and Position #	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.74	12.42	314	5609	392	954.5
7-2	3.04	13.86	232	5911	406	977.0
7-3	2.58	14.34	189	6016	360	-

%Carbon in Solid Sample = 3.66

Combustion Efficiency = 99.1%

Heat Removal Rate = 131,523 Btu/hr.

Test No. : 3 Date: May 25, 1989

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/ hr

Flowrates:

Primary Air: 40 scfm
Secondary Air: 35 scfm
Tertiary Air: 51 scfm
Coal : 1.12 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.3	13.70	373	5300	331	945.7
7-2	2.50	14.42	871	5456	355	970.2
7-3	2.40	15.26	282	5687	358	-

%Carbon in Solid Sample = 3.78

Combustion Efficiency = 99.1%

Heat Removal Rate = 142,911 Btu/hr

Test No. : 4 Date: May 25, 1989

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/ hr

Flowrates:

Primary Air:	40 scfm
Secondary Air:	86 scfm
Tertiary Air:	---
Coal :	1.12 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.78	12.34	121	5627	394	906.9
7-2	3.10	13.16	121	5981	408	931.2
7-3	2.84	13.24	117	5872	434	-

%Carbon in Solid Sample = 3.01

Combustion Efficiency = 99.2%

Heat Removal Rate = 107,007 Btu/hr.

Test No. : 5 Date: May 29, 1989

Type of Coal: Minto

Firing Rate: 1.0 X 10^6 Btu/ hr

Flowrates:

Primary Air: 42 scfm
Secondary Air: 136 scfm
Tertiary Air: 33 scfm
Coal : 1.46 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	4.02	12.50	238	5696	516	1099.4
7-2	3.72	12.60	940	5744	546	1127.6
7-3	3.54	12.58	587	5755	549	--

%Carbon in Solid Sample = 2.55

Combustion Efficiency = 99.4%

Heat Removal Rate = 211,899 Btu/hr

Test No. : 6 Date: May 31, 1989

Type of Coal: Minto

Firing Rate: 1.0 X 10^6 Btu/ hr

Flowrates:

Primary Air:	42 scfm
Secondary Air:	85 scfm
Tertiary Air:	85 scfm
Coal :	1.68 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.94	12.54	148	5855	403	1079.5
7-2	3.30	12.90	513	6156	395	1086.3
7-3	2.82	14.70	852	6454	414	--

%Carbon in Solid Sample = 3.76

Combustion Efficiency = 99.1%

Heat Removal Rate = 195,000 Btu/hr

Test No. : 7 Date: May 31, 1989

Type of Coal: Minto

Firing Rate: 1.0 X 10^6 Btu/ hr

Flowrates:

Primary Air: 42 scfm
Secondary Air: 126 scfm
Tertiary Air: 42 scfm
Coal : 1.68 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.80	12.65	570	5760	476	1059.6
7-2	2.37	13.83	475	6193	442	1054.7
7-3	3.37	12.87	400	5938	491	--

%Carbon in Solid Sample = 3.43

Combustion Efficiency = 99.1%

Heat Removal Rate = 195,000 Btu/hr

Test No. : 8 Date: June 1, 1989

Type of Coal: Devco

Firing Rate: 1.0 X 10^6 Btu/ hr

Flowrates:

Primary Air: 41 scfm
Secondary Air: 93 scfm
Tertiary Air: 75 scfm
Coal : 1.41 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.38	15.32	258	866	406	1119.9
7-2	2.30	17.22	726	898	408	1143.0
7-3	2.18	17.03	186	901	420	--

%Carbon in Solid Sample = 2.67

Combustion Efficiency = 99.8%

Heat Removal Rate = --

Test No. : 9

Date: June 16, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/ hr

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	1.11 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	4.74	12.26	-	769	433	775.9
7-2	3.46	13.42	-	834	469	984.0
7-3	3.52	14.24	-	796	493	-

%Carbon in Solid Sample = 1.73

Combustion Efficiency = 99.9%
Heat Removal Rate = 156,758 Btu/hr

Test No. : 10 Date: June 19, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/ hr

Flowrates:

Primary Air: 40 scfm
Secondary Air: 60 scfm
Tertiary Air: 25 scfm
Coal : 1.06 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	4.36	13.02	120	814	329	749.0
7-2	2.00	17.80	618	936	359	994.3
7-3	1.18	18.44	704	919	463	--

%Carbon in Solid Sample = 1.70

Combustion Efficiency = 99.9%

Heat Removal Rate = 169,437 Btu/hr

Test No. : 11 Date: June 20, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/ hr

Flowrates:

Primary Air: 40 scfm
Secondary Air: 77 scfm
Tertiary Air: 10 scfm
Coal : 1.11 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	4.06	13.06	-	816	481	1006.0
7-2	2.00	17.20	325	878	544	1074.0
7-3	1.82	17.50	454	860	498	--

%Carbon in Solid Sample = 7.29
Combustion Efficiency = 99.8%
Heat Removal Rate = 239,299 Btu/hr

Test No. : 12 Date: June 21, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/ hr

Flowrates:

Primary Air: 45 scfm
Secondary Air: 30 scfm
Tertiary Air: 50 scfm
Coal : 1.10 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	4.64	12.62	-	752	420	922.0
7-2	3.08	15.30	-	835	444	953.0
7-3	2.76	16.10	-	826	440	--

%Carbon in Solid Sample = 1.17

Combustion Efficiency = 99.8%

Heat Removal Rate = 258,689 Btu/hr

Test No. : 13 Date: June 22, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/ hr

Flowrates:

Primary Air: 45 scfm
Secondary Air: 55 scfm
Tertiary Air: 25 scfm
Coal : 0.95 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	6.58	11.48	-	668	545	908.3
7-2	4.42	12.76	-	759	591	964.3
7-3	4.30	12.46	-	690	626	-

%Carbon in Solid Sample = -

Combustion Efficiency = -

Heat Removal Rate = 240,281 Btu/hr

Test No. : 14 Date: July 20, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/ hr

Flowrates:

Primary Air: 50 scfm
Secondary Air: 25 scfm
Tertiary Air: 50 scfm
Coal : 1.17 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	4.92	11.34	-	625	471	918.0
7-2	3.74	12.72	-	695	486	954.0
7-3	3.14	14.80	-	690	500	--

%Carbon in Solid Sample = -

Combustion Efficiency = -

Heat Removal Rate = -

Test No. : 15 Date: July 25, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/ hr

Flowrates:

Primary Air:	40 scfm
Secondary Air:	60 scfm
Tertiary Air:	25 scfm
Coal :	1.05 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	6.24	10.24	-	599	431	989.3
7-2	4.10	11.34	-	683	496	1063.0
7-3	3.30	12.54	-	671	566	--

%Carbon in Solid Sample = -

Combustion Efficiency = -

Heat Removal Rate = -

Test No. : 16 Date: August 8, 1989

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/ hr

Type of Limestone Feed: Blended

Ca/S Ratio: 1.8

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	1.2 lb/min
Limestone:	0.42 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.2	14.9	3/8	2985	429	943
7-2	2.9	15.8	1486	4185	424	1002
7-3	2.5	15.5	2230	2394	432	-
6-1	-	-	-	-	-	1023
6-2	-	-	-	-	-	1057
6-3	-	-	-	-	-	-
5-1	3.8	13.2	141	2870	350	1049
5-2	3.4	14.7	849	3210	389	1156
5-3	3.2	14.9	1790	3082	374	-

TEST NO: 16 (Cont'd)

% Carbon in Solid Sample: 0.58

Combustion Efficiency: 98.6%

Heat Removal Rate: 209,900 Btu/hr

% Sulfur Capture (Gas Side) = 37.3

% Sulfur Capture (Solid Sample - Method 1) = 19.9

% Sulfur Capture (Fly Ash - Method 1) = 17.1

% Sulfur Capture (Bottom Ash - Method 1) = 44.2

% Sulfur Capture (Solid Sample - Method 2) = 22.7

% Sulfur Capture (Fly Ash - Method 2) = 18.4

% Sulfur Capture (Bottom Ash - Method 2) = 44.0

% Sulfur Capture (Solid Side - Method 3) = 27.4

% $CaCO_3$ Reacted to $CaSO_4$ = 13.5

% $CaCO_3$ Unreacted = 0.67

Test No. : 17 Date: August 10, 1989

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/ hr

Type of Limestone Feed: Blended

Ca/S Ratio: 3.3

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	1.07 lb/min
Limestone:	0.75 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.8	15.1	36	2268	457	914
7-2	3.5	15.1	33	2277	484	940
7-3	3.2	16.6	768	1310	471	-
6-1	-	-	-	-	-	878
6-2	-	-	-	-	-	905
6-3	-	-	-	-	-	-
5-1	6.1	10.8	-	1075	421	963
5-2	3.9	16.1	1538	2673	489	982
5-3	3.5	16.8	1734	1380	488	-

TEST NO: 17 (Cont'd)

% Carbon in Solid Sample: 0.82

Combustion Efficiency: 99.3%

Heat Removal Rate: 132,600 Btu/hr

% Sulfur Capture (Gas Side) = 62.5

% Sulfur Capture (Solid Sample - Method 1) = 37.4

% Sulfur Capture (Fly Ash - Method 1) = 32.3

% Sulfur Capture (Bottom Ash - Method 1) = 53.5

% Sulfur Capture (Solid Sample - Method 2) = 47.4

% Sulfur Capture (Fly Ash - Method 2) = 35.0

% Sulfur Capture (Bottom Ash - Method 2) = 66.5

% Sulfur Capture (Solid Side - Method 3) = 39.5

% $CaCO_3$ Reacted to $CaSO_4$ = 16.9

% $CaCO_3$ Unreacted = 1.08

Test No. : 18 Date: August 21, 1989

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/ hr

Type of Limestone Feed: Blended

Ca/S Ratio: 4.8

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	1.13 lb/min
Limestone:	1.17 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	2.9	16.6	528	2164	401	951
7-2	2.1	17.3	3283	3151	388	956
7-3	1.9	17.2	2505	2034	403	-
6-1	-	-	-	-	-	929
6-2	-	-	-	-	-	965
6-3	-	-	-	-	-	-
5-1	4.0	16.4	31	978	300	964
5-2	2.9	16.4	54	2793	409	989
5-3	3.2	16.5	-	1614	363	-

TEST NO: 18 (Cont'd)

% Carbon in Solid Sample: 1.09

Combustion Efficiency: 98.8%

Heat Removal Rate: 153,840 Btu/hr

% Sulfur Capture (Gas Side) = 56.9

% Sulfur Capture (Solid Sample - Method 1) = 49.0

% Sulfur Capture (Fly Ash - Method 1) = 44.1

% Sulfur Capture (Bottom Ash - Method 1) = 83.8

% Sulfur Capture (Solid Sample - Method 2) = 63.7

% Sulfur Capture (Fly Ash - Method 2) = 51.7

% Sulfur Capture (Bottom Ash - Method 2) = 92.8

% Sulfur Capture (Solid Side - Method 3) = 51.6

% $CaCO_3$ Reacted to $CaSO_4$ = 16.7

% $CaCO_3$ Unreacted = 1.5

Test No. : 19 Date: August 23, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Blended

Ca/S Ratio: 2.1

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	0.95 lb/min
Limestone:	0.066 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.1	15.20	-	283	396	963
7-2	2.8	15.7	176	398	416	1013
7-3	2.3	16.6	255	409	422	-
6-1	-	-	-	-	-	1022
6-2	-	-	-	-	-	1096
6-3	-	-	-	-	-	-
5-1	3.7	15.3	166	431	417	1050
5-2	2.6	16.4	2782	529	460	1183
5-3	2.2	16.6	144	452	480	-

TEST NO: 19 (Cont'd)

% Carbon in Solid Sample: 1.82

Combustion Efficiency: 99.8%

Heat Removal Rate: 136,853 Btu/hr

% Sulfur Capture (Gas Side) = 55.8 %

% Sulfur Capture (Solid Sample - Method 1) = 32.8

% Sulfur Capture (Fly Ash - Method 1) = 31.5

% Sulfur Capture (Bottom Ash - Method 1) = 54.3

% Sulfur Capture (Solid Sample - Method 2) = 44.8

% Sulfur Capture (Fly Ash - Method 2) = 29.7

% Sulfur Capture (Bottom Ash - Method 2) = 50.0

% Sulfur Capture (Solid Side - Method 3) = 32.7

% $CaCO_3$ Reacted to $CaSO_4$ = 22.3

% $CaCO_3$ Unreacted = 11.8

Test No. : 20 Date: August 30, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Blended

Ca/S Ratio: 3.3

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	1.08 lb/min
Limestone:	0.11 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.0	15.4	25	203	394	962
7-2	2.2	16.7	76	338	432	998
7-3	1.5	16.9	298	151	444	-
6-1	-	-	-	-	-	1022
6-2	-	-	-	-	-	1029
6-3	-	-	-	-	-	-
5-1	-	-	-	-	-	1018
5-2	-	-	-	-	-	1081
5-3	-	-	-	-	-	-

TEST NO: 20 (Cont'd)

% Carbon in Solid Sample: 1.34

Combustion Efficiency: 99.9%

Heat Removal Rate: 196,440 Btu/hr

% Sulfur Capture (Gas Side) = 68.4

% Sulfur Capture (Solid Sample - Method 1) = 19.4

% Sulfur Capture (Fly Ash - Method 1) = 33.1

% Sulfur Capture (Bottom Ash - Method 1) = 52.7

% Sulfur Capture (Solid Sample - Method 2) = 23.1

% Sulfur Capture (Fly Ash - Method 2) = 30.6

% Sulfur Capture (Bottom Ash - Method 2) = 61.0

% Sulfur Capture (Solid Side - Method 3) = 38.5

% $CaCO_3$ Reacted to $CaSO_4$ = 8.8

% $CaCO_3$ Unreacted = 6.9

Test No. : 21 Date: September 1, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/ hr

Type of Limestone Feed: Blended

Ca/S Ratio: 3.9

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	1.09 lb/min
Limestone:	0.134 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.4	15.3	17	126	402	954
7-2	2.8	16.5	702	320	435	982
7-3	2.5	16.2	2498	271	368	-
6-1	-	-	-	-	-	956
6-2	-	-	-	-	-	1048
6-3	-	-	-	-	-	-
5-1	-	-	-	-	-	1026
5-2	-	-	-	-	-	1158
5-3	-	-	-	-	-	-

TEST NO: 21 (Cont'd)

% Carbon in Solid Sample: 1.00

Combustion Efficiency: 99.9%

Heat Removal Rate: 145,568 Btu/hr

% Sulfur Capture (Gas Side) = 66.0

% Sulfur Capture (Solid Sample - Method 1) = 13.4

% Sulfur Capture (Fly Ash - Method 1) = 33.6

% Sulfur Capture (Bottom Ash - Method 1) = 68.2

% Sulfur Capture (Solid Sample - Method 2) = 17.7

% Sulfur Capture (Fly Ash - Method 2) = 29.3

% Sulfur Capture (Bottom Ash - Method 2) = 81.9

% Sulfur Capture (Solid Side - Method 3) = 60.9

% $CaCO_3$ Reacted to $CaSO_4$ = 4.6

% $CaCO_3$ Unreacted = 1.7

Test No. : 22 Date: September 12, 1989

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Burner Injection

Ca/S Ratio: 1.6

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	1.24 lb/min
Limestone:	0.45 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.5	15.2	46	4714	393	933
7-2	2.9	16.4	882	5239	405	970
7-3	2.4	16.7	1634	5053	384	-
6-1	-	-	-	-	-	980
6-2	-	-	-	-	-	1020
6-3	-	-	-	-	-	-
5-1	-	-	-	-	-	1002
5-2	-	-	-	-	-	1102
5-3	-	-	-	-	-	-

TEST NO: 22 (Cont'd)

% Carbon in Solid Sample: 6.92

Combustion Efficiency: 94.3%

Heat Removal Rate: 179,124 Btu/hr

% Sulfur Capture (Gas Side) = 12.7

% Sulfur Capture (Solid Sample - Method 1) = 21.1

% Sulfur Capture (Fly Ash - Method 1) = 19.2

% Sulfur Capture (Bottom Ash - Method 1) = 47.5

% Sulfur Capture (Solid Sample - Method 2) = 24.0

% Sulfur Capture (Fly Ash - Method 2) = 18.2

% Sulfur Capture (Bottom Ash - Method 2) = 46.5

% Sulfur Capture (Solid Side - Method 3) = 32.5

% $CaCO_3$ Reacted to $CaSO_4$ = 14.4

% $CaCO_3$ Unreacted = 1.5

Test No. : 23 Date: September 13, 1989

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Burner Injection

Ca/S Ratio: 2.7

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	1.17 lb/min
Limestone:	0.65 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%C_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.6	14.9	769	3545	279	893
7-2	3.2	16.1	307	3368	366	909
7-3	2.8	16.5	287	2569	397	-
6-1	-	-	-	-	-	961
6-2	-	-	-	-	-	989
6-3	-	-	-	-	-	-
5-1	-	-	-	-	-	973
5-2	-	-	-	-	-	1007
5-3	-	-	-	-	-	-

TEST NO: 23 (Cont'd)

% Carbon in Solid Sample: 6.42

Combustion Efficiency: 94.2%

Heat Removal Rate: 152,910 Btu/hr

% Sulfur Capture (Gas Side) = 38.9

% Sulfur Capture (Solid Sample - Method 1) = 22.6

% Sulfur Capture (Fly Ash - Method 1) = 22.8

% Sulfur Capture (Bottom Ash - Method 1) = 24.6

% Sulfur Capture (Solid Sample - Method 2) = 27.2

% Sulfur Capture (Fly Ash - Method 2) = 14.8

% Sulfur Capture (Bottom Ash - Method 2) = 65.7

% Sulfur Capture (Solid Side - Method 3) = 16.6

% $CaCO_3$ Reacted to $CaSO_4$ = 10.2

% $CaCO_3$ Unreacted = 2.9

Test No. : 24 Date: September 14, 1989

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Burner Injection

Ca/S Ratio: 3.5

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	1.28 lb/min
Limestone:	0.96 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.9	13.6	0	3331	323	943
7-2	3.3	16.9	1299	3372	339	987
7-3	2.4	17.1	2520	3228	364	-
6-1	-	-	-	-	-	977
6-2	-	-	-	-	-	989
6-3	-	-	-	-	-	-
5-1	-	-	-	-	-	980
5-2	-	-	-	-	-	1000
5-3	-	-	-	-	-	-

TEST NO: 24 (Cont'd)

% Carbon in Solid Sample: 1.88

Combustion Efficiency: 97.9%

Heat Removal Rate: 95,620 Btu/hr

% Sulfur Capture (Gas Side) = 35.7

% Sulfur Capture (Solid Sample - Method 1) = 40.7

% Sulfur Capture (Fly Ash - Method 1) = 27.0

% Sulfur Capture (Bottom Ash - Method 1) = 58.9

% Sulfur Capture (Solid Sample - Method 2) = 47.6

% Sulfur Capture (Fly Ash - Method 2) = 23.6

% Sulfur Capture (Bottom Ash - Method 2) = 42.3

% Sulfur Capture (Solid Side - Method 3) = 29.6

% $CaCO_3$ Reacted to $CaSO_4$ = 13.8

% $CaCO_3$ Unreacted = 1.2

Test No. : 25 Date: September 26, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Burner Injection

Ca/S Ratio: 1.9

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	0.98 lb/min
Limestone:	0.06 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	4.6	12.4	0	403	367	905
7-2	3.7	13.4	792	562	390	963
7-3	3.2	15.3	0	506	415	-
6-1	-	-	-	-	-	959
6-2	-	-	-	-	-	1016
6-3	-	-	-	-	-	-
5-1	-	-	-	-	-	976
5-2	-	-	-	-	-	1085
5-3	-	-	-	-	-	-

TEST NO: 25 (Cont'd)

% Carbon in Solid Sample: 10.9

Combustion Efficiency: 98.9%

Heat Removal Rate: 126,634 Btu/hr

% Sulfur Capture (Gas Side) = 26.2

% Sulfur Capture (Solid Sample - Method 1) = 26.2

% Sulfur Capture (Fly Ash - Method 1) = 24.1

% Sulfur Capture (Bottom Ash - Method 1) = 58.9

% Sulfur Capture (Solid Sample - Method 2) = 30.5

% Sulfur Capture (Fly Ash - Method 2) = 17.4

% Sulfur Capture (Bottom Ash - Method 2) = 69.3

% Sulfur Capture (Solid Side - Method 3) = 19.1

% $CaCO_3$ Reacted to $CaSO_4$ = 17.8

% $CaCO_3$ Unreacted = 5.1

Test No. : 26 Date: September 29, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/ hr

Type of Limestone Feed: Burner Injection

Ca/S Ratio: 2.8

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	0.99 lb/min
Limestone:	0.09 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	2.8	16.3	428	340	300	924
7-2	2.4	16.2	456	486	318	983
7-3	2.7	16.3	0	376	413	-
6-1	-	-	-	-	-	944
6-2	-	-	-	-	-	1041
6-3	-	-	-	-	-	-
5-1	-	-	-	-	-	985
5-2	-	-	-	-	-	1100
5-3	-	-	-	-	-	-

TEST NO: 26 (Cont'd)

% Carbon in Solid Sample: 3.81

Combustion Efficiency: 99.6%

Heat Removal Rate: 156,940 Btu/hr

% Sulfur Capture (Gas Side) = 45.4

% Sulfur Capture (Solid Sample - Method 1) = 24.9

% Sulfur Capture (Fly Ash - Method 1) = 23.9

% Sulfur Capture (Bottom Ash - Method 1) = 43.1

% Sulfur Capture (Solid Sample - Method 2) = 22.4

% Sulfur Capture (Fly Ash - Method 2) = 26.2

% Sulfur Capture (Bottom Ash - Method 2) = 50.9

% Sulfur Capture (Solid Side - Method 3) = 34.7

% $CaCO_3$ Reacted to $CaSO_4$ = 11.3

% $CaCO_3$ Unreacted = 5.5

Test No. : 27 Date: October 2, 1989

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Burner Injection

Ca/S Ratio: 4.2

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	75 scfm
Coal :	1.1 lb/min
Limestone:	0.16 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	4.2	13.2	0	123	388	947
7-2	3.3	17.3	60	133	431	997
7-3	2.9	17.8	562	100	429	-
6-1	-	-	-	-	-	1001
6-2	-	-	-	-	-	1054
6-3	-	-	-	-	-	-
5-1	-	-	-	-	-	1009
5-2	-	-	-	-	-	1103
5-3	-	-	-	-	-	-

TEST NO: 27 (Cont'd)

% Carbon in Solid Sample: 2.55

Combustion Efficiency: 99.7%

Heat Removal Rate: 155,207 Btu/hr

% Sulfur Capture (Gas Side) = 83.1

% Sulfur Capture (Solid Sample - Method 1) = 14.7

% Sulfur Capture (Fly Ash - Method 1) = 13.8

% Sulfur Capture (Bottom Ash - Method 1) = 26.7

% Sulfur Capture (Solid Sample - Method 2) = 14.7

% Sulfur Capture (Fly Ash - Method 2) = 14.5

% Sulfur Capture (Bottom Ash - Method 2) = 34.4

% Sulfur Capture (Solid Side - Method 3) = -

% $CaCO_3$ Reacted to $CaSO_4$ = 5.0

% $CaCO_3$ Unreacted = 8.9

Test No. : 28 Date: August 1, 1989

Type of Coal: Devco

Firing Rate: 1.0 X 10^6 Btu/ hr

Type of Limestone Feed: -

Ca/S Ratio: -

Flowrates:

Primary Air: 42 scfm
Secondary Air: 125 scfm
Tertiary Air: 42 scfm
Coal : 1.3 lb/min
Limestone: -

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	4.6	12.7	0	763	592	1011
7-2	3.6	13.3	0	815	658	1031
7-3	3.6	12.9	147	817	634	1029
6-1	-	-	-	-	-	1053
6-2	-	-	-	-	-	1083
6-3	-	-	-	-	-	1061
5-1	-	-	-	-	-	1102
5-2	-	-	-	-	-	1158
5-3	-	-	-	-	-	1137

TEST NO: 28 (Cont'd)

% Carbon in Solid Sample: 7.73

Combustion Efficiency: 99.8%

Heat Removal Rate: 162,685 Btu/hr

% Sulfur Capture (Gas Side) = -

% Sulfur Capture (Solid Sample - Method 1) = -

% Sulfur Capture (Fly Ash - Method 1) = -

% Sulfur Capture (Bottom Ash - Method 1) = -

% Sulfur Capture (Solid Sample - Method 2) = -

% Sulfur Capture (Fly Ash - Method 2) = -

% Sulfur Capture (Bottom Ash - Method 2) = -

% Sulfur Capture (Solid Side - Method 3) = -

% $CaCO_3$ Reacted to $CaSO_4$ = -

% $CaCO_3$ Unreacted = -

Test No. : 29 Date: 10 January, 1990

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Blended

Ca/S Ratio: 3.0

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	1.06 lb/min
Limestone:	0.74

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	3.6	16.4	0	2371	361	933
7-2	3.1	17.2	216	2501	369	958
7-3	2.6	17.9	372	2089	377	952
6-1	3.9	13.8	0	2286	323	1011
6-2	3.3	15.4	0	2278	355	1038
6-3	2.8	17.2	0	1992	395	1038
5-1	4.8	12.4	0	1853	285	1045
5-2	3.4	15.8	2637	3568	356	1107
5-3	2.9	17.0	2299	2405	280	1103

TEST NO: 29 (Cont'd)

% Carbon in Solid Sample: 1.71

Combustion Efficiency: 98.4%

Heat Removal Rate: 128,946 Btu/hr

% Sulfur Capture (Gas Side) = 59.7

% Sulfur Capture (Solid Sample - Method 1) = 31.5

% Sulfur Capture (Fly Ash - Method 1) = 29.0

% Sulfur Capture (Bottom Ash - Method 1) = 60.9

% Sulfur Capture (Solid Sample - Method 2) = 35.2

% Sulfur Capture (Fly Ash - Method 2) = 26.8

% Sulfur Capture (Bottom Ash - Method 2) = 70.6

% Sulfur Capture (Solid Side - Method 3) = 35.2

% $CaCO_3$ Reacted to $CaSO_4$ = 14.3

% $CaCO_3$ Unreacted = 1.9

Test No. : 30 Date: January 18, 1990

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Blended

Ca/S Ratio: 2.9

Flowrates:

Primary Air:	40 scfm
Secondary Air:	35 scfm
Tertiary Air:	50 scfm
Coal :	1.07 lb/min
Limestone:	0.11

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	2.6	17.8	0	315	324	945
7-2	2.4	17.7	237	330	343	977
7-3	2.3	17.9	0	291	307	971
6-1	2.4	18.1	0	320	319	1014
6-2	2.4	17.1	353	312	305	1047
6-3	2.3	17.9	94	318	323	1036
5-1	2.9	15.8	0	380	360	1057
5-2	2.7	16.9	0	350	351	1133
5-3	2.7	17.1	0	338	369	1118

TEST NO: 30 (Cont'd)

% Carbon in Solid Sample: 3.63

Combustion Efficiency: 99.6%

Heat Removal Rate: 164,776 Btu/hr

% Sulfur Capture (Gas Side) = 60.4

% Sulfur Capture (Solid Sample - Method 1) = 40.4

% Sulfur Capture (Fly Ash - Method 1) = 33.0

% Sulfur Capture (Bottom Ash - Method 1) = 66.9

% Sulfur Capture (Solid Sample - Method 2) = 39.4

% Sulfur Capture (Fly Ash - Method 2) = 26.9

% Sulfur Capture (Bottom Ash - Method 2) = 68.7

% Sulfur Capture (Solid Side - Method 3) = 43.8

% $CaCO_3$ Reacted to $CaSO_4$ = 18.3

% $CaCO_3$ Unreacted = 4.2

Test No. : 31 Date: February 8, 1990

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Downstream Injection

Ca/S Ratio: -

Flowrates:

Primary Air:	40 scfm
Secondary Air:	60 scfm
Tertiary Air:	25 scfm
Coal :	1.08 lb/min
Limestone:	-

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	6.1	11.0	0	7271	129	932
7-2	3.5	13.0	0	7878	128	950
7-3	1.5	17.1	556	7998	131	947
6-1	6.8	10.9	0	4645	108	1002
6-2	3.7	12.5	0	7055	118	1026
6-3	0.8	18.1	8595	7996	106	1019
5-1	7.8	10.6	0	4317	100	1041
5-2	6.9	10.9	0	6181	105	1098
5-3	1.6	17.0	8225	7997	126	1110

TEST NO: 31 (Cont'd)

% Carbon in Solid Sample: 7.1

Combustion Efficiency: 98.4%

Heat Removal Rate: 201,320 Btu/hr

% Sulfur Capture (Gas Side) = -

% Sulfur Capture (Solid Sample - Method 1) = -

% Sulfur Capture (Fly Ash - Method 1) = -

% Sulfur Capture (Bottom Ash - Method 1) = -

% Sulfur Capture (Solid Sample - Method 2) = -

% Sulfur Capture (Fly Ash - Method 2) = -

% Sulfur Capture (Bottom Ash - Method 2) = -

% Sulfur Capture (Solid Side - Method 3) = -

% $CaCO_3$ Reacted to $CaSO_4$ = -

% $CaCO_3$ Unreacted = -

Test No. : 32 Date: February 13, 1990

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Downstream Injection

Ca/S Ratio: 1.5

Flowrates:

Primary Air:	40 scfm
Secondary Air:	60 scfm
Tertiary Air:	25 scfm
Coal :	1.1 lb/min
Limestone:	0.35

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	6.3	11.9	0	3845	146	763
7-2	4.1	12.6	0	3883	150	806
7-3	3.3	13.4	0	4167	151	796
6-1	6.6	11.9	0	3851	134	815
6-2	4.4	12.7	0	4461	139	856
6-3	3.3	13.9	1003	4555	151	841
5-1	7.5	11.9	0	2276	124	891
5-2	5.6	12.9	0	2789	141	904
5-3	4.7	13.3	0	3146	155	900

TEST NO: 32 (Cont'd)

% Carbon in Solid Sample: 4.47

Combustion Efficiency: 96.2%

Heat Removal Rate: 165,911 Btu/hr

% Sulfur Capture (Gas Side) = 25.2

% Sulfur Capture (Solid Sample - Method 1) = 32.6

% Sulfur Capture (Fly Ash - Method 1) = 38.9

% Sulfur Capture (Bottom Ash - Method 1) = 41.8

% Sulfur Capture (Solid Sample - Method 2) = 24.4

% Sulfur Capture (Fly Ash - Method 2) = 24.2

% Sulfur Capture (Bottom Ash - Method 2) = 31.3

% Sulfur Capture (Solid Side - Method 3) = 14.0

% $CaCO_3$ Reacted to $CaSO_4$ = 22.2

% $CaCO_3$ Unreacted = 43.1

Test No. : 33 Date: February 14, 1990

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Downstream Injection

Ca/S Ratio: 2.9

Flowrates:

Primary Air:	40 scfm
Secondary Air:	60 scfm
Tertiary Air:	25 scfm
Coal :	1.1 lb/min
Limestone:	0.71

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	5.4	12.3	0	2349	133	878
7-2	3.5	14.5	0	2616	146	956
7-3	2.4	15.4	0	2254	168	932
6-1	5.9	12.3	0	2466	158	1008
6-2	3.5	13.9	549	2813	161	1034
6-3	2.6	15.2	938	3296	152	1016
5-1	6.8	11.6	0	3885	111	1013
5-2	5.5	12.4	0	3933	127	1051
5-3	3.5	14.5	0	3970	139	1023

TEST NO: 33 (Cont'd)

% Carbon in Solid Sample: 3.49

Combustion Efficiency: 96.2%

Heat Removal Rate: 163,782 Btu/hr

% Sulfur Capture (Gas Side) = 57.3

% Sulfur Capture (Solid Sample - Method 1) = 41.8

% Sulfur Capture (Fly Ash - Method 1) = 39.3

% Sulfur Capture (Bottom Ash - Method 1) = 42.8

% Sulfur Capture (Solid Sample - Method 2) = 51.0

% Sulfur Capture (Fly Ash - Method 2) = 45.9

% Sulfur Capture (Bottom Ash - Method 2) = 53.4

% Sulfur Capture (Solid Side - Method 3) = 45.1

% $CaCO_3$ Reacted to $CaSO_4$ = 18.9

% $CaCO_3$ Unreacted = 10.3

Test No. : 34 Date: February 19, 1990

Type of Coal: Minto

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Downstream Injection

Ca/S Ratio: 3.6

Flowrates:

Primary Air:	40 scfm
Secondary Air:	60 scfm
Tertiary Air:	25 scfm
Coal :	1.1 lb/min
Limestone:	0.91 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	6.4	12.2	0	1069	115	898
7-2	3.6	15.4	397	1439	103	916
7-3	2.4	17.6	2969	1593	106	903
6-1	6.9	11.9	0	1087	97	982
6-2	3.7	13.5	151	1399	104	996
6-3	2.8	15.2	712	1633	103	984
5-1	7.2	12.0	0	988	99	986
5-2	4.4	13.3	0	1190	122	1064
5-3	3.3	15.4	0	1532	115	1026

TEST NO: 34 (Cont'd)

% Carbon in Solid Sample: 1.5

Combustion Efficiency: 98.1%

Heat Removal Rate: 188,576 Btu/hr

% Sulfur Capture (Gas Side) = 77.2

% Sulfur Capture (Solid Sample - Method 1) = 50.2

% Sulfur Capture (Fly Ash - Method 1) = 53.5

% Sulfur Capture (Bottom Ash - Method 1) = 51.9

% Sulfur Capture (Solid Sample - Method 2) = 59.9

% Sulfur Capture (Fly Ash - Method 2) = 52.9

% Sulfur Capture (Bottom Ash - Method 2) = 65.5

% Sulfur Capture (Solid Side - Method 3) = 58.6

% $CaCO_3$ Reacted to $CaSO_4$ = 18.9

% $CaCO_3$ Unreacted = 6.2

Test No. : 35 Date: February 22, 1990

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: -

Ca/S Ratio: -

Flowrates: -

Primary Air: 40 scfm
Secondary Air: 60 scfm
Tertiary Air: 25 scfm
Coal : 1.0 lb/min
Limestone:

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	4.8	12.4	0	885	144	963
7-2	3.0	15.7	0	914	156	985
7-3	2.1	17.7	0	973	156	976
6-1	6.1	11.7	0	657	147	991
6-2	3.0	14.9	511	861	167	1037
6-3	2.0	18.2	3015	965	153	1019
5-1	7.7	10.3	0	608	142	1011
5-2	4.3	12.8	0	767	156	1086
5-3	3.1	15.0	0	896	163	1071

TEST NO: 35 (Cont'd)

% Carbon in Solid Sample: 12.4

Combustion Efficiency: 99.7%

Heat Removal Rate: 179,092 Btu/hr

% Sulfur Capture (Gas Side) = -

% Sulfur Capture (Solid Sample - Method 1) = -

% Sulfur Capture (Fly Ash - Method 1) = -

% Sulfur Capture (Bottom Ash - Method 1) = -

% Sulfur Capture (Solid Sample - Method 2) = -

% Sulfur Capture (Fly Ash - Method 2) = -

% Sulfur Capture (Bottom Ash - Method 2) = -

% Sulfur Capture (Solid Side - Method 3) = -

% $CaCO_3$ Reacted to $CaSO_4$ = -

% $CaCO_3$ Unreacted = -

Test No. : 36 Date: February 23, 1990

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Downstream Injection

Ca/S Ratio: 2.2

Flowrates:

Primary Air:	40 scfm
Secondary Air:	60 scfm
Tertiary Air:	25 scfm
Coal :	1.07 lb/min
Limestone:	0.084 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	%O_2	%CO_2	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	5.0	12.5	0	355	143	918
7-2	3.1	15.5	0	378	148	946
7-3	2.3	17.8	1037	462	134	932
6-1	6.2	11.9	0	364	151	989
6-2	3.3	16.3	336	449	177	1031
6-3	2.3	17.4	1299	477	186	1016
5-1	8.5	9.9	0	298	142	1034
5-2	4.3	12.2	0	412	176	1106
5-3	3.1	15.7	0	437	190	1081

TEST NO: 36 (Cont'd)

% Carbon in Solid Sample: 11.6

Combustion Efficiency: 98.7 %

Heat Removal Rate: 186,395 Btu/hr

% Sulfur Capture (Gas Side) = 50.9

% Sulfur Capture (Solid Sample - Method 1) = 22.3

% Sulfur Capture (Fly Ash - Method 1) = 21.0

% Sulfur Capture (Bottom Ash - Method 1) = 41.7

% Sulfur Capture (Solid Sample - Method 2) = 27.8

% Sulfur Capture (Fly Ash - Method 2) = 22.9

% Sulfur Capture (Bottom Ash - Method 2) = 47.8

% Sulfur Capture (Solid Side - Method 3) = 36.7

% $CaCO_3$ Reacted to $CaSO_4$ = 13.8

% $CaCO_3$ Unreacted = 0.59

Test No. : 37 Date: February 26, 1990

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Downstream Injection

Ca/S Ratio: 2.8

Flowrates:

Primary Air:	40 scfm
Secondary Air:	60 scfm
Tertiary Air:	25 scfm
Coal :	0.98 lb/min
Limestone:	0.096 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	5.5	12.0	0	239	149	891
7-2	3.6	13.4	0	270	141	932
7-3	2.4	16.3	139	295	137	917
6-1	6.5	11.6	0	217	146	933
6-2	3.7	13.4	0	310	166	1008
6-3	2.1	18.0	1662	372	169	978
5-1	7.7	9.3	0	150	119	995
5-2	5.7	11.6	0	197	163	1056
5-3	3.5	17.4	1013	308	162	1029

TEST NO: 37 (Cont'd)

% Carbon in Solid Sample: 5.21

Combustion Efficiency: 99.4%

Heat Removal Rate: 183,464 Btu/hr

% Sulfur Capture (Gas Side) = 64.7

% Sulfur Capture (Solid Sample - Method 1) = 27.9

% Sulfur Capture (Fly Ash - Method 1) = 30.5

% Sulfur Capture (Bottom Ash - Method 1) = 52.2

% Sulfur Capture (Solid Sample - Method 2) = 26.9

% Sulfur Capture (Fly Ash - Method 2) = 26.7

% Sulfur Capture (Bottom Ash - Method 2) = 65.1

% Sulfur Capture (Solid Side - Method 3) = 38.4

% $CaCO_3$ Reacted to $CaSO_4$ = 13.5

% $CaCO_3$ Unreacted = 19.9

Test No. : 38 Date: March 1, 1990

Type of Coal: Devco

Firing Rate: 0.6 X 10^6 Btu/hr

Type of Limestone Feed: Downstream Injection

Ca/S Ratio: 4.1

Flowrates:

Primary Air:	40 scfm
Secondary Air:	60 scfm
Tertiary Air:	25 scfm
Coal :	1.2 lb/min
Limestone:	0.18 lb/min

Gas Concentration and Temperature Profile:

Port# and Position#	$\%O_2$	$\%CO_2$	ppm CO	ppm SO_2	ppm NO_x	Temp (°C)
7-1	4.8	12.4	0	153	146	949
7-2	2.9	15.5	0	236	139	964
7-3	2.2	18.3	740	267	156	950
6-1	5.9	12.3	0	142	119	1008
6-2	3.7	15.9	710	213	144	1037
6-3	2.3	18.0	1243	246	150	1023
5-1	8.9	9.9	0	111	105	1051
5-2	5.2	12.7	73	193	135	1121
5-3	2.9	15.5	0	226	145	1101

TEST NO: 38 (Cont'd)

% Carbon in Solid Sample: 5.63

Combustion Efficiency: 99.0%

Heat Removal Rate: 179,462 Btu/hr

% Sulfur Capture (Gas Side) = 71.6

% Sulfur Capture (Solid Sample - Method 1) = 35.7

% Sulfur Capture (Fly Ash - Method 1) = 35.4

% Sulfur Capture (Bottom Ash - Method 1) = 74.6

% Sulfur Capture (Solid Sample - Method 2) = 31.3

% Sulfur Capture (Fly Ash - Method 2) = 29.9

% Sulfur Capture (Bottom Ash - Method 2) = 93.2

% Sulfur Capture (Solid Side - Method 3) = 52.7

% $CaCO_3$ Reacted to $CaSO_4$ = 11.8

% $CaCO_3$ Unreacted = 31.0

NEW

Appendix B

Typical Fuel and Sorbent Analysis

Typical Analysis of Minto and Devco Coal:

Ultimate Analysis of Coals (wt %)

Sample	C	H	N	S	O	Ash	Moisture
Minto	65.88	4.50	0.68	7.12	3.56	17.27	0.99
Devco	81.37	5.36	1.60	1.11	6.65	2.37	1.54

Proximate Analysis of Coals (wt %)

Sample	Moisture	Ash	Volatile Matter
Minto	0.99	17.27	31.80
Devco	1.54	2.37	32.63

Calorific Value of Coals

Sample	Btu/lb
Minto	12,208
Devco	14,539

Sieve Analysis of Coals

Size	Minto (wt %)	Devco (wt %)
> 0.5 mm	0	0
> 0.3 mm < 0.5 mm	0	0
> 0.15 mm < 0.3 mm	3.3	0
> 0.075 mm < 0.15 mm	23.3	3.03
> 0.045 mm < 0.075 mm	20.0	15.15
> 0.038 mm < 0.045 mm	6.7	12.12
< 0.038 mm	46.7	69.70

Analysis of Limestone
(wt %)

CaO	55.61
MgO	0.53
Fe_2O_3	0.23
%Acid Insol.	2.38

Sieve Analysis of Limestone

Size	wt %
> 0.85 mm	2.44
> 0.5 mm < 0.85 mm	2.44
> 0.3 mm < 0.5 mm	0
> 0.15 mm < 0.3 mm	2.44
> 0.075 mm < 0.15 m	4.88
> 0.045 mm < 0.075 mm	9.76
< 0.045 mm	78.05

Appendix C

Sample Calculation - Ca/S Ratio Determination

Sample Calculation - Using Test No. 23

Nominal Ca/S Ratio = 3.0

Type of Limestone Feed = Burner Injection

$$1.17 \frac{\text{lb coal}}{\text{min}} \times 0.0633 \frac{\text{lb S}}{\text{lb Coal}} = 0.0741 \frac{\text{lb S}}{\text{min}}$$

$$\frac{0.0741 \text{ lbS/min}}{32 \text{ lb S/lb molS}} = 0.0023 \frac{\text{lb mol S}}{\text{min}}$$

$$0.65 \frac{\text{lb limestone}}{\text{min}} \times 0.96 \frac{\text{lb } CaCO_3}{\text{lb limestone}} = 0.624 \frac{\text{lb } CaCO_3}{\text{min}}$$

$$0.624 \frac{\text{lb } CaCO_3}{\text{min}} \times \frac{40 \text{ lb Ca}}{100 \text{ lb} CaCO_3} \times \frac{1 \text{ lbmol Ca}}{40 \text{ lb Ca}} = 0.00624 \frac{\text{lbmol Ca}}{\text{min}}$$

Therefore: $\frac{Ca}{S} = \frac{0.00624}{0.0023} = 2.7$

Appendix D

Sample Calculation - Combustion Efficiency Determination

Sample Calculation Using Test No. 1

Heat available with fuel in:

heating value of coal = 12,162 Btu/lb
flowrate of coal = 1.14 lb/min

$$12{,}162 \frac{\text{Btu}}{\text{lb}} \text{ X } 1.14 \frac{\text{lb}}{\text{min}} = 13{,}865 \frac{\text{Btu}}{\text{min}}$$

Heat available with carbon out:

% ash in coal = 20
% C in ash = 2.76

$$\text{flowrate of ash} = \frac{0.2}{1\text{-}0.0276} \text{ X } 1.14 = 0.23 \frac{\text{lb}}{\text{min}}$$

heating value of carbon = 14,600 Btu/lb

$$14{,}600 \frac{\text{Btu}}{\text{lb}} \text{ X } 0.23 \frac{\text{lb}}{\text{min}} \text{ X } 0.0276 = 92.7 \frac{\text{Btu}}{\text{min}}$$

$$\text{Therefore: Combustion Efficiency} = \frac{13\ 865 - 92.7}{13\ 865} \text{ X } 100\%$$

$$= 99.3\%$$

Appendix E

Sulfur Capture Computer Program - Gas Side and Solid Side Determination (Method 1)

```
B2: "CHATHAM CFB DEMONSTRATION PROJECT CALCULATIONS
A5: ^INPUT DATA:
A6: ^===========
A7: 'Ca/S ratio:
C7: 2
A8: "Coal Analysis : %C
C8: 63.62
D8: "Limestone Analysis:
B9: "        %H
C9: 4.48
E9: "      %CaO
F9: 53.5
B10: "        %N
C10: 0.84
E10: "      %MgO
F10: 2.44
B11: "        %S
C11: 6.4
E11: "    %Fe2O3
F11: 0.17
B12: "        %O
C12: 4.29
E12: "     %SiO2
F12: 2.68
B13: "      %Ash
C13: 19.6
B14: "%Moisture
C14: 0.78
A16: ^Vol. %O2 in stack:
C16: 4
D16: ^
F16: ^
A17: ^SO2 in stack:(ppm)
C17: 3800
A19: ^Ash Analysis: wt % unburnt carbon:
E19: 1
B20: ^     wt % unreacted CaCO3:
E20: 10
B21: ^
C21: ^      wt % CaSO4:
E21: 20
A23: "=============================================================================
A24: ^OUTPUT DATA:
A25: ^===========
A26: "Basis: 100 lbs coal
A28: ^Converted Limestone Analysis:
E28: ^    %CaCO3
F28: (F9)+(F9)*44.0088/56.0794
E29: ^    %MgCO3
F29: (F10)+(F10)*44.0088/40.3114
E30: ^    %Fe2O3
F30: +F11
E31: ^     %SiO2
F31: +F12
A33: ^Final Limestone Analysis:
E33: ^    %CaCO3
```

```
F33: (F29)*100/((F29)+(F29)+(F30)+(F31))
A34: ^Basis of 100%
E34: ^    %MgCO3
F34: (F29)*100/((F29)+(F29)+(F30)+(F31))
E35: ^    %Fe2O3
F35: (F30)*100/((F29)+(F29)+(F30)+(F31))
E36: ^     %SiO2
F36: (F31)*100/((F29)+(F29)+(F30)+(F31))
A38: ^Limestone Flowrate on 100 lb Coal Flow Basis:
F38: ((C11)+(C7)+100.0882/32.06)/((F33)*0.01)
A40: ^Total Solids Generated by Combustion Process:
B41: ^
C41: ^Ash from Coal:
E41: (+C13)
F41: ^lbs
A42: ^
B42: ^ Inerts from Limestone:
E42: (F38)*((F35)+(F36))/100
F42: ^lbs
A43: ^
B43: ^     CaO from Limestone:
E43: (F39)*(F33)*56.074/(100*100.0892)
F43: ^lbs
B44: ^     MgO from Limestone:
E44: (F38)*(F34)*40.31/(100*84.31)
F44: ^lbs
A45: ^
B45: ^CO2 in Unreacted CaCO3:
E45: 0.01*(E30)*((E41)+(E42)+(E43)+(E44)+(E45)+(E46)+(E47))/2.27427696
F45: ^lbs
B46: ^
C46: ^ SO3 in CaSO4:
E46: 0.01*(E31)*((E41)+(E42)+(E43)+(E44)+(E45)+(E46)+(E47))/1.7004829
F46: ^lbs
B47: ^ Unburnt Carbon in Ash:
E47: 0.01*(E19)*((E41)+(E42)+(E43)+(E44)+(E45)+(E46)+(E47))
F47: ^lbs
D48: ^
E48: ^==========
D49: ^Total:
E49: (E41)+(E42)+(E43)+(E44)+(E45)+(E46)+(E47)
F49: ^lbs
A51: ^% of Carbon Unburnt in Coal:
E51: (E47)*100/(C8)
A52: ^% of Carbon Burnt:
E52: 100-(E51)
A53: ^% of CaCO3 Unreacted:
E53: (100.0882*100*(E45)/44.0088)/((F38)*(F33)/100)
A54: ^% CaCO3 Reacted to CaSO4:
E54: ((E46)*136.1376*100/80.0582)/((F38)*(F33)/100)
A55: ^% S Capture Based on Solids:
E55: ((E46)*32.06*100/80.0582)/(C11)
A58: ^Coal:
B59: ^lbs
C59: ^lbmoles
A60: ^C
```

```
C60: (B60)/12.010572
A61: ^H
B61: (C9)
C61: (B61)/1.008
A62: ^N
B62: (C10)
C62: (B62)/14.01
A63: ^S
B63: (C11)
C63: (B63)/32.06
A64: ^O
B64: (C12)
C64: (B64)/15.9994
A65: ^H2O
B65: (C14)
C65: (B65)/18.0154
B66: ^
A67: ^Limestone:
B68: ^lbs
C68: ^lbmoles
A69: ^CaCO3
B69: (F33)*(F38)/100
C69: (B69)/100.0862
A70: ^MgCO3
B70: (F34)*(F38)/100
C70: (B70)/84.3202
A72: ^O2 Required for Combustion:
D72: (C60)+(C61)/4+(C63)-(C64)/2
E72: ^lbmoles
A74: ^
A75: ^SO2 CAPTURE BASED
A76: ^ON O2 ANALYSIS:
A77: ^==============
A79: ^Volume %O2 in Stack Gas:
D79: (C16)
A81: ^STACK GAS:
B83: ^Dry Basis
C83: ^%
D83: ^ppm
A85: ^O2
B85: (0.79/0.21*(D72)+(C60)+(C63)+(C69)+(C70))/(100/(D79)-4.7619048)
C85: (B85)*100/((B85)+(B86)+(B87)+(B88))
D85: (F0) (C85)*10000
A86: ^N2
B86: 0.79*((B85)+(D72))/0.21
C86: (B86)*100/((B85)+(B86)+(B87)+(B88))
D86: (F0) (C86)*10000
A87: ^CO2
B87: (C60)+(C69)+(C70)-(E45)/44.0088
C87: (B87)*100/((B85)+(B86)+(B87)+(B88))
D87: (F0) (C87)*10000
A88: ^SO2
R   B88: (C11)/32.06
    C88: (B88)*100/((B85)+(B86)+(B87)+(B88))
    D88: (F0) (C88)*10000
R

    A90: ^% S Capture:
    C90: ((D88)-(C17))*100/(D88)
```

CHATHAM LOW NOX DEMONSTRATION PROJECT CALCULATIONS

INPUT DATA:

Ca/S ratio:	3.000			
Coal Analysis :	%C	66.150	Limestone Analysis:	
	%H	4.550	%CaO	51.950
	%N	0.950	%MgO	0.520
	%S	6.320	%Fe2O3	0.260
	%O	3.230	%SiO2	2.420
	%Ash	17.530		
	%Moisture	1.190		
Vol. %O2 in stack:		3.460		
SO2 in stack: (ppm)		1951.670		
Ash Analysis: wt % unburnt carbon:			0.850	
wt % unreacted CaCO3:			0.330	
wt % CaSO4:			14.790	

OUTPUT DATA:

Basis: 100 lbs coal

Converted Limestone Analysis:	%CaCO3	92.718
	%MgCO3	1.088
	%Fe2O3	0.260
	%SiO2	2.420
Final Limestone Analysis:	%CaCO3	96.095
Basis of 100%	%MgCO3	1.127
	%Fe2O3	0.269
	%SiO2	2.508

Limestone Flowrate on 100 lb Coal Flow Basis: 61.597 lbs

Total Solids Generated by Combustion Process:

Ash from Coal:	17.530	lbs
Inerts from Limestone:	1.711	lbs
CaO from Limestone:	33.162	lbs
MgO from Limestone:	0.332	lbs
CO2 in Unreacted CaCO3:	0.085	lbs
SO3 in CaSO4:	5.105	lbs
Unburnt Carbon in Ash:	0.499	lbs
Total:	58.423	lbs

% of Carbon Unburnt in Coal:	0.754
% of Carbon Burnt:	99.246
% of CaCO3 Unreacted:	0.327
% CaCO3 Reacted to CaSO4:	14.665
% S Capture Based on Solids:	32.344

Coal:

	lbs	lbmoles
C	66.150	5.508
H	4.530	4.514
N	0.980	0.070
S	6.320	0.197
O	3.280	0.205
H2O	1.190	0.066

Limestone:

	lbs	lbmoles
CaCO3	59.191	0.591
MgCO3	0.694	0.008

O2 Required for Combustion: 6.731 lbmoles

SO2 CAPTURE BASED ON O2 ANALYSIS:

Volume %O2 in Stack Gas: 3.460

STACK GAS:

	Dry Basis	%	ppm
O2	1.310	3.461	34612
N2	30.249	79.918	799178
CO2	6.094	16.100	161001
SO2	0.197	0.521	5208

% S Capture: 62.527

Appendix F

Sample Calculation - Sulfur Capture Determination
Solid Side
(Method 2)

Sample Calculation Using Test No. 16

Ca/S Ratio In = 1.8

From ash analysis of solid sample:

Total S = 2.93%
Total Ca = 29.04%

$$\frac{Ca}{S} = \frac{0.2904/40 \text{ lb/lbmol}}{0.0293/32 \text{ lb/lbmol}}$$

$$= 7.93$$

$$\text{Therefore } \%S \text{ Capture} = \frac{1.8}{7.93} \times 100$$

$$= 22.7 \%$$

Appendix G

Sample Calculation - Sulfur Capture Determination - Solid Side (Method 3)

Sample Calculation Using Test No: 16

Coal Analysis: 16.72% ash
25.63% Fe
6.0 % S

Coal Flow = 1.2 lb/min

Therefore: Fe flow = (1.2)(0.1672)(0.2563) = 0.051 $\frac{\text{lbFe}}{\text{min}}$

Limestone Analysis: 37.81% Ca
0.18 % Fe

Limestone flow = 0.42 lb/min

Therefore Ca flow = (0.42)(0.3781) = 0.16 $\frac{\text{lb Ca}}{\text{min}}$

Fe flow = (0.42)(0.0018) = 0.00076 $\frac{\text{lb Fe}}{\text{min}}$

Fly Ash Analysis:	4.60 % C	11.15 % Fe
X lb/min	0% $CaCO_3$	30.67 % Ca
	9.90 % $CaSO_4$	2.51 % S
Bottom Ash Analysis :	1.51 % C	7.44 % Fe
Y lb/min	4.49 % $CaCO_3$	28.96 % Ca
	23.97 % $CaSO_4$	5.67 % S

Solids Generated in Each Ash Stream:

Let a = unburnt C in fly ash
b = unburnt C in bottom ash
c = CO_2 in unreacted $CaCO_3$ from limestone in fly ash
d = CO_2 in unreacted $CaCO_3$ from limestone in bottom ash
e = SO_3 in $CaSO_4$ which reacted in fly ash
f = SO_3 in $CaSO_4$ which reacted in bottom ash

Carbon in Fly Ash	Carbon in Bottom Ash
$\frac{a}{x} = 0.046$	$\frac{b}{y} = 0.0151$

Unreacted $CaCo_3$ in Fly Ash

$$\frac{c\{\frac{100.09}{44.01}\}}{X} = 0$$

Unreacted $CaCO_3$ in Bottom Ash

$$\frac{d\{\frac{100.09}{44.01}\}}{y} = 0.0449$$

Reacted to $CaSO_4$ in Fly Ash

$$\frac{c\{\frac{136.14}{80.06}\}}{X} = 0.099$$

Reacted to $CaSO_4$ in Bottom Ash

$$\frac{f\{\frac{136.14}{80.06}\}}{y} = 0.2397$$

Fe Balance: $0.051 + 0.00076 = X\ (0.1115) + Y\ (0.0744)$

Ca Balance: $0.16 = X\ (0.3067) + Y\ (0.2896)$

Using a computer program to solve eight equations with eight unknowns gives:

a = 0.0153
b = 0.003
c = 0
d = 0.004
e = 0.0194
f = 0.0281
x = 0.333
y = 0.1997

$$\text{S in with coal} = 1.2 \frac{\text{lb coal}}{\text{min}} \times 0.06 \frac{\text{lb S}}{\text{lb coal}}$$
$$= 0.072 \text{ lb S/min}$$

$$\text{S out with ash} = (0.333 \frac{\text{lb fly ash}}{\text{min}})(0.0251 \frac{\text{lb S}}{\text{lb fly ash}})$$
$$+ (0.1997 \frac{\text{lb bottom ash}}{\text{min}})(0.0567 \frac{\text{lb S}}{\text{lb bottom ash}})$$
$$= 0.0197 \text{ lb S/min}$$

$$\text{Therefore: \% Sulfur Capture} = \frac{0.0197}{0.072} \times 100$$

$$= 27.4\ \%$$

Appendix H

Sample Calculation: Concentration of SO_2 in Stack Gas as a Function of Sulfur in Coal

Coal Analysis:
(Basis: 100 lb)

	lb	lbmols	lbmols O_2 required
C	63.62	5.297	5.297
H	4.48	4.48	1.12
N	0.84	0.060	
O	4.28	0.268	-0.134
H_2O	0.78	0.043	
S	6.00	0.187	0.187
ash	20.00		
			6.47

with 25% excess air

total O_2 required = (1.25)(6.47) = 8.09 lb mols

$$\text{total } N_2 = 8.09 \text{ X } \frac{79}{21} = 30.43 \text{ lbmols}$$

Stack Gas Consists of:

	Air	Coal	Total
O_2	1.62	-	1.62
N_2	30.43	0.03	30.46
CO_2	-	5.297	5.297
H_2O	-	2.24 + 0.043	2.283
SO_2	-	0.187	0.187
			39.85

Therefore: concentration of SO_2 in the stack gas firing coal with a 6% Sulfur content

$$= \frac{0.187}{39.85} \text{ X } 10^6 = 4{,}693 \text{ ppm}$$

Appendix I

Sample Calculation - Theoretical Flame Temperature with the Addition of Limestone Versus Heat Removal Rate

Analysis of coal:
(Basis: 100 kg)

	Kg	Kgmols	Kgmols O_2 required
C	63.62	5.30	5.30
H	4.48	4.48	1.12
N	0.84	0.06	
S	6.40	0.20	0.20
O	4.28	0.268	-0.134
ash	19.6		
moisture	0.78	0.04	
			6.49 kgmols

With 25% excess air

Total O_2 required = (6.49)(1.25) = 8.11 kgmols

Total $N_2 = 8.11 \times \frac{79}{21} = 30.51$ kgmols

Stack Gas Consists of:

	Air	Coal	Total
O_2	1.62	-	1.62
N_2	30.51	0.03	30.54
CO_2	-	5.30	5.30
SO_2	-	0.20	0.20
H_2O	-	2.24 + 0.04	2.28
			39.94 kgmols

HHV of coal = 11,494 Btu/lb
= 6636 kcal/kg

Amount of H_2O in Stack Gas = 2.28 kgmols
41.08 kg

Heat of condensation of H_2O at 25° C = 1050.4 Btu/lb
= 583.6 kcal/kg

Therefore: Heat of condensation $= \frac{(583.6)(41.08)}{100}$

$= 240$ cal/g

LHV = 6636 - 240 = 6396 cal/g

Adiabatic Flame Temperature: assume Tad = 2000 °C

	kgmols	Cp	mCp
N_2	30.54	8.00	244.32
O_2	1.62	8.40	13.61
CO_2	5.30	13.10	69.43
H2O	2.28	10.45	23.83
SO_2	O.2	13.00	2.60
ash	19.6	0.2	3.92
			357.71

$$\Delta T = \frac{(100)(6396)}{357.71} = 1788\ ^\circ C$$

Therefore T = 1788 °C + 25°C = 1813 °C

Therefore assume Tad = 1825 °C

	m	Cp	mCp
N_2	30.54	7.90	241.27
O_2	1.62	8.35	13.53
CO_2	5.30	12.95	68.64
H_2O	2.28	10.25	23.37
SO_2	0.2	13.0	2.60
ash	19.6	0.2	3.92
			353.33

$$\Delta T = \frac{(100)(6396)}{353.33} = 1810\ ^\circ C$$

Therefore T = 1835°C

Therefore: the adiabatic flame temperature = 1835 °C

Remove 100,000 $\frac{Btu}{hr}$ out of 600,000 $\frac{Btu}{hr}$

$$\Delta H = (6396)(\frac{5}{6}) = 5330 \text{ kcal/kg}$$

$$\text{for same } C_p : \Delta T = \frac{(100)(5330)}{353.33}$$

$$= 1509 \text{ °C}$$

Therefore T = 1534 °C

	m	C_p	mC_p
N_2	30.54	7.75	236.38
O_2	1.62	8.20	13.28
CO_2	5.30	12.65	67.05
H_2O	2.28	9.90	22.57
SO_2	0.2	12.5	2.50
ash	19.6	0.2	3.92
			345.70

$$\Delta T = \frac{(100)(5330)}{345.70} = 1542 \text{ °C}$$

T = 1567 °C

Therefore: The flame temperature when 100,000 Btu/hr is removed = 1567 °C (2853 °F)

With a Ca/S Ratio of 2.0 determine the theoretical flame temperature

Analysis of Limestone (wt %)	$CaCO_3$	92.32
	$MgCO_3$	4.93
	Fe_2O_3	0.16
	%Acid Insol	2.59

S in coal = 0.2 kgmols

Amount of Ca required for Ca/S = 2.0 : 0.4 kgmols

Therefore: Amount of $CaCO_3$ required = 0.4 X 100.09
= 40.04 kg

Amount of limestone required $= \frac{40.04}{0.9232}$

= 43.37 kg

Amount of $MgCO_3$ in required amount of limestone

= (43.37)(0.0493)
= 2.14 kg

	kg	kgmols	kgmols CO_2 formed
$CaCO_3$	40.04	0.40	0.40
$MgCO_3$	2.14	0.025	0.025
inerts	1.19	-	---
			0.425

mass of ash :	CaO	20.83
	MgO	0.92
	inerts	1.19
		22.94

Therefore: Stack gas consists of:

	Air	Coal	Limestone	Total
N_2	30.54	0.03	-	30.57
O_2	1.62	-	-	1.62
CO_2	-	5.30	0.425	5.73
H_2O	-	2.28	-	2.28
SO_2	-	0.20	-	0.20
ash	-	19.6	22.9	42.50

ΔH_{CaCO_3} = (-151.9) - (94.0518) - (-288.45)
= 42.5 kcal/kgmol

ΔH_{MGCO_3} = (-143.84) - (94.0518) - (-261.70)
= 23.80 kcal/kgmol .

ΔH_{TOTAL} = (100)(6396) - (0.4)(42,500) - (0.025)(23,800)
= 622,500 kcal/100 kg

Assume T = 1775 °C

	m	cp	mCp
N_2	30.57	7.90	240.95
O_2	1.62	8.30	13.44
CO_2	5.73	12.85	73.63
H_2O	2.28	10.20	23.26
SO_2	0.20	13.0	2.60
ash	42.50	0.2	8.50
			362.38

$$\Delta T = \frac{622\,500}{362.38} = 1718\ °C$$

Therefore: Theoretical flame temperature with the addition of limestone at a Ca/S ratio of 2.0 is 1743 °C (3169 °F)

If 50% of the SO_2 reacts, determine the flame temperature:

$$CaO + SO_2 + 1/2\ O_2 \rightarrow CaSO_4$$

ΔH = -342.42 - 1/2 (O) - (-70.96) - (- 151.90)
= -119.56 kcal/kgmol
= 11,956 kcal/100 kg

ΔH_{TOTAL} = 622,500 + 11,956 = 634,456 $\frac{kcal}{100\ kg}$

$$\Delta T = \frac{634\,456}{362.38} = 1751°C$$

Therefore: T = 1776 °C

Therefore: If 50% of the SO_2 reacts the theoretical flame temperature is 1776°C (3229°F), an increase of 33°C (59°F) over the theoretical flame temperature if all the SO_2 reacts.